



BACHELOR THESIS & COLLOQUIUM - ME 141502

**DEVELOPMENT OF A SIMULINK MODEL TO INVESTIGATE FUEL  
CONSUMPTION AND EFFICIENCY OF A MAIN FUEL ENGINE**

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DOUBLE DEGREE PROGRAM

MARINE ENGINEERING DEPARTMENT

FACULTY OF MARINE TECHNOLOGY

INSTITUT TEKNOLOGI SEPULUH NOPEMBER

SURABAYA 2018



## **BACHELOR THESIS – ME 141502**

### **Development of a Simulink Model to Investigate Fuel Consumption and Efficiency of a Main Fuel Engine**

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DOUBLE DEGREE PROGRAM OF  
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Surabaya  
2018



**APPROVAL FORM**  
**“DEVELOPMENT OF A SIMULINK MODEL TO INVESTIGATE FUEL**  
**CONSUMPTION AND EFFICIENCY OF A MAIN FUEL ENGINE”**  
**BACHELOR THESIS**

Submitted to Comply One of the Requirement to Obtain a Bachelor of  
Engineering

on

Department of Marine Engineering

Faculty of Marine Technology

Institut Teknologi Sepuluh Nopember

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Warnemünde,

July 2018

## **APPROVAL FORM**

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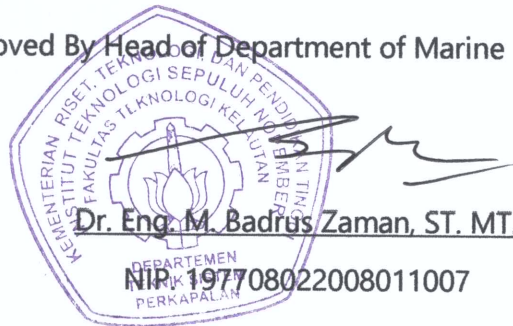
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Surabaya,

August 2018

## **Executive Summary**

Marine Business is one of the largest business in the world. Exports and Imports of human's necessities in majority are using ships. This is because the ratio between the goods that can be delivered in each trip and the number of trips it can go to fulfill this. This makes the shipping or transport cost-efficient. But the continuous growth of the world population and its standard of living creates an ever increasing dependency for the world economy on international trade. Therefore a good shipping company will always develop a better way of shipping together with more efficient and optimized voyage planning.

To increase the efficiency of shipping, companies tries to reduce the cost of almost everything. Therefore, one of the options for increasing the efficiency of a shipping is by increasing the efficiency of the ship itself. The ship efficiency is not only determined by how fast the ship and how much the ship can load, but also how much fuel does the ship consume for each operation. An investigation of the engine efficiency must be done. The investigation will be done by using an engine model in Simulink to create a similar engine model to the real engine. Then simulate the dynamic process of the engine, which will affect the consumption in general. Therefore the consumption of the engine can be analyzed.

The results of this bachelor thesis is an explanation of how to develop the engine model. This includes the explanation of what is the engine efficiency, and the engine parameters that affect the efficiency, such as the engine consumption, engine losses, etc. The model development includes the change in parameters and model structure. Then a simulation is done to compare the results with the measured data. From this process, the model can be considered satisfactory when the results are similar to the measured data.

***Keyword: Simulink, Engine Efficiency, Engine Consumption, Engine Parameters, Development.***

# DECLARATION OF HONOR

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This final project report has written without any plagiarism act, and confirm consciously that all the data, concepts, design, references, and material in this report own by Hochschule Wismar department of Maritime Studies which are the product of research study and reserve the right to use for further research study and its development.

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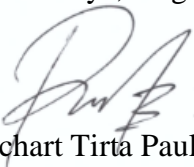
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INVESTIGATE FUEL CONSUMPTION AND  
EFFICIENCY OF A MAIN FUEL ENGINE

Department : Double Degree Program of Marine Engineering

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Surabaya, August 2018



Richart Tirta Paulalengan

## **PREFACE**

The author would like to thank God for His grace and blessings that was given to the author, so the author can finish this Bachelor Thesis titled "Development of a Simulink Model to Investigate Fuel Consumption and Efficiency of a Main Fuel Engine."

This Bachelor Thesis is submitted to comply for one of the requirement to obtain the Bachelor of Engineering Degree in Double Degree Program Department of Marine Engineering, Faculty of Marine Technology, Institut Teknologi Sepuluh Nopember – Hochschule Wismar, Germany. There were so many obstacles that the author had during the process for finishing the Bachelor Thesis. So, it's necessary for the author to say some gratitude for anyone who support the author during this process.

1. My beloved Father and Mother, my brothers and all my family who always give me support and motivation whenever I need to look forward for my success.
2. Prof. Dr.-Ing Axel Rafoth and Dr.-Ing Wolfgang Busse as my 1<sup>st</sup> Supervisor and 2<sup>nd</sup> Supervisor in Rostock, Germany for the support and guidance during the process of my Bachelor Thesis.
3. I Made Ariana, S.T., M.T., Dr.-MarSc. as my supervisor in Institut Teknologi Sepuluh Nopember Surabaya, who gives me suggestions in the beginning of the process.
4. All of my friends, especially, Robby Rachmat Susilo, Reinhart Yosafat and Dion Arman Lilipaly, for supporting me, helping me, giving advice and suggestion and also motivating me during the process of Bachelor Degree.

Hopefully, this Bachelor Thesis can help readers to expand their knowledge and give inspiration for whoever needs it. Author realizes that this Thesis is not perfect, so the author is looking forward for any suggestions and critics for further development in writing skills.

Rostock, July 5th, 2018

Author



# Scope of Bachelor-thesis

For Mr. Richart Tirta Paulalengan  
Matriculation Number:

Topic: Development of a Simulink Model to Investigate Fuel  
Consumption and Efficiency of a Main Fuel Engine.

Date of issue of Bachelor thesis : March 2018

Date of delivery of Bachelor thesis : July 2018

Supervisor:	Prof. Dr.-Ing. Axel Rafoth	Hochschule Wismar
	Dr.-Ing. Wolfgang Busse	Hochschule Wismar

## Scope

For simulating overall system energy efficiency in ships propulsion systems a model of a fuel engine should be developed. This model based only on energy transfer has to show dependency of efficiency from operating point, speed and load torque. To a certain degree non optimal fuel injection in dynamic behavior should be implemented and checked for different engines.

All values used as a parameter for operation and losses should be derived from machine data or load test report. This requires a model of combustion machine and its control as well as loss components like pending pumps and friction.

To validate this model, signal outputs for main engine components like fuel rack position or specific power consumption have to be supplied.

The part models and the overall system have to be compared and adjusted to measured data from main engine in building 5.

Note: It would be suitable to have a Simulink/Matlab license at the laptop of the student.

Prof. Dr.-Ing. Axel Rafoth

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## **CHAPTER I**

### **INTRODUCTION**

#### **1.1. BACKGROUND**

The continuous growth of the world population and its standard of living creates an ever increasing dependency for the world economy on international trade. Therefore a good shipping company will always develop a better way of shipping together with more efficient and optimized voyage planning. Other than that, there is an economical factor that must be fulfilled to make the shipping cost-efficient.

One of the options for increasing the efficiency of a shipping is by increasing the efficiency of the main engine itself. For a certain travel distance, the engine will work in a random or dynamic state. This creates a random condition for the engine load, torque and the consumption itself. For whatever the distance of the travel, the consumption of the engine is the main reason whether or not the ship can be called efficient. Therefore, an investigation of the engine efficiency is often done many times.

Developments nowadays are based on models and designs that are created and simulated under certain parameters. A thorough understanding of how the engine operates is important in this matter. By that information, a simulated formula of the system can be obtained. The simulation will be done under various conditions while the ship is on voyage. This is done by adapting the existing model of a diesel engine to present the influence of power/speed change to fuel consumption. When this is done, the next step will be to try to use the data from the simulation to find a structured procedure to derive a suitable coefficient for the model. From this model, another simulation of the engine running under dynamic operation can be fulfilled. This simulation of a running engine will result in a similar condition of the engine while in operation at sea.

The simulation for this thesis is done by using MATLAB/Simulink. This program is designed to help understand and create various systems using blocks and diagrams. For the engine operation, the data that are going to be used is the systems for the engine operation itself such as the injection systems, combustion process, etc. The use of existing model of diesel engine is helpful due to a complex task that have to be done in creating a new and running diesel engine model. This model will only be based on energy transfer and has to show the dependency of efficiency from an operating point, speed and load torque. The non-optimal fuel injection will serve as a dynamic behavior where it should be implemented and checked for different engines. This is done by deriving data of operation parameters and losses from an actual machine data or load test reports. This requires an actual model of combustion machine and its control as well as losses parameters such as connected pumps and friction. For this thesis, the model will be modified to suit the parameters of an actual engine.

There should be a measured data from an actual engine that can be used to validate the model. Signal outputs such as the fuel rack position or specific power have to be supplied to the model. The simulated data from the simulation will be used to determine what the engine behavior under these conditions and loads are. These will generate a graphic or diagram that will show data such as an engine propeller matching diagram would. From this point, an optimization of the system can be determined.

## **1.2. STATEMENT OF PROBLEMS**

Based on the description above the statement of problem of this thesis are;

1. How to modify an engine model to be running as similar to the real engine?
2. What parameters are affecting engine efficiency?
3. How is the fuel consumption affected?

### **1.3. RESEARCH LIMITATIONS**

The limitations of this thesis are;

1. The model used is a pre-created model of a diesel engine.
2. This research will use MATLAB/Simulink as a supporting program.

### **1.4. RESEARCH OBJECTIVES**

The objectives of this thesis are;

1. To modify and simulate a diesel engine model to run as a real engine would do.
2. To investigate the fuel consumption and efficiency of the engine model.
3. To compare the fuel consumption and efficiency from the model with the real engine data.

### **1.5. RESEARCH BENEFITS**

1. Provides information diesel engine model.
2. Provides information of diesel engine parameters.
3. Provides better understanding in Simulink model modification.
4. Provides information about fuel consumption and their differences between conditions.





## **CHAPTER II**

### **LITERATURE STUDY**

#### **2.1. General Diesel Engine Theories**

Engines are machineries that are used to generate power. This power can be used for various purpose, such as generating electricity, generating thrust, etc. There are some types of engines such as diesel engine, gasoline engine, turbine engine, steam engine, electric motor, etc. These engines are commonly used worldwide and they have their own advantages and disadvantages. For example, the diesel engine gives high torque but low speed compared to gasoline engine which will produce higher speed but less torque. This comparison is of course done in the parameters of the same size of engine. Other engine such as turbine engine will generate high power with the cost of high fuel consumption. For this thesis, the engine that will be discussed is the diesel engine.

Diesel engines are invented by Rudolf Diesel. The diesel engine is an internal combustion engine that uses the heat and pressure of the compression to ignite the fuel mixture. Mechanical components such as spark plugs, coils are not required for ignition. Because as the piston moves upwards, it compresses the air until such degree that the temperature will increase from the pressure. This heat is sufficient to ignite the fuel that are injected, therefore the fuel injected will be ignited as soon as it is injected. Despite the difference in the ignition process, the whole engine components, from diesel and gasoline engine, are pretty much alike. They both have an engine block, cylinder liner, crankshaft, pistons, camshaft, connecting rods, and valve train. They both also require lubrication system and cooling system to operate.

Both diesel engine and gasoline engine have 4 steps of combustion. The sequence are the same which is expansion, compression, power stroke and

exhaust stroke. The expansion stroke is the time where the engine gets the air from the intake manifold. In this stroke, the piston moves downward while the intake valve opens. Then there is the compression stroke. This stroke is when the piston moves upward to compress the mixture of air and fuel. After that the combustion occurs and the power stroke begins. This happens because the power from the ignition moves piston downward to produce torque which is transferred to the crankshaft. This power is enough to move the piston back upward while the exhaust valve opens. This stroke is called the exhaust stroke because in this stroke the exhaust gas is blown out. As gasoline engines have 2 type of cycles, the diesel engine also have 2 types of cycles. Those are 2 stroke and 4 stroke cycles. The principal of 2 strokes and 4 strokes are the same. The 2 stroke engine completes their whole cycle from expansion-compression-power-exhaust stroke in 2 rounds of cycle. So the exhaust stroke are done at the same time as the power stroke. For 4 stroke engine, each stroke are done individually.

Marine Propulsion plants are complicated system with hull, engine and propeller operating together. Diesel engines are very important components of the system and are highly non-linear and time-invariant. Therefore the modelling of diesel engines is one of the key problem for simulations and control of the system. These simulations can be used for various purposes, such as machinery performance analysis, ship performance, maneuvering analysis and machinery control development.

To understand how to model an engine system, an understanding of how the engine actually works are needed. The figure below is the schematic diagram of a propulsion system of a ship. The diagram focuses on the engine system.

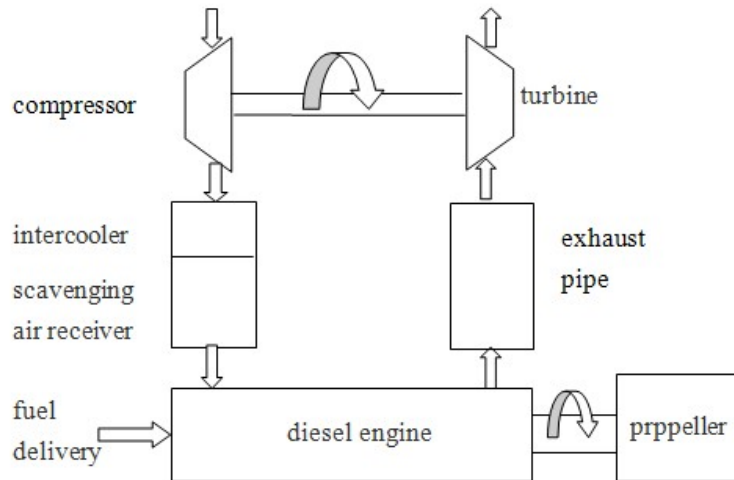


Figure 1. Engine System Schematic Diagram

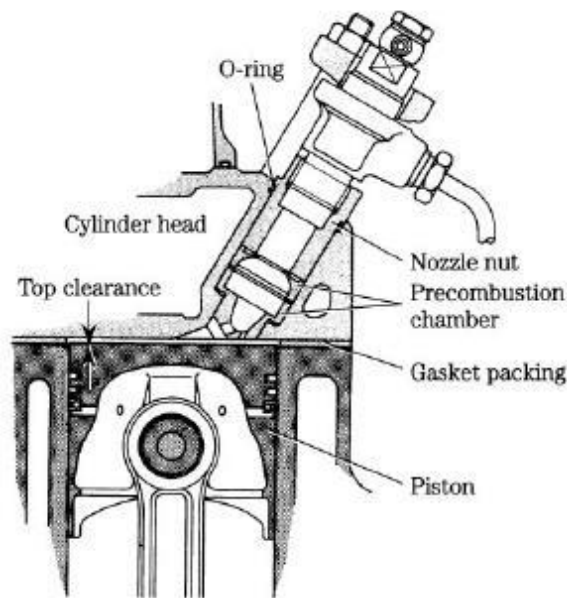
Source: *Modeling and Simulation of Working Process of Marine Diesel Engine with a Comprehensive Method*

From that diagram, the process of an engine operation are determined by various inputs such as the fuel, air intake, exhaust, and propeller or loads that are connected to the engine. This system are a rough explanation of the engine system as a whole.

## 2.2. Combustion in Diesel Engine

In the diesel engine, the air is compressed with a compression ratio of from 15:1 to 23:1. Then the liquid fuel is sprayed by fuel injector located near to the top-center of the piston into the combustion chamber. The pressure and temperature of air inside the cylinder are very high enough to trigger some chemical reaction when the fuel is injected into the cylinder. On the other hand, the chemical reaction may start so slowly in diesel engine. This is called the delay period. (1; 2)

As the absence of an ignition spark, the ignition process in diesel engine can't be controlled to set when and where to ignite. Ignition depends on high compression ratio. It will set the gases inside the combustion chamber to be above the temperature and pressure needed for starting the combustion process. (1; 2)



*Figure 2. Diesel Engine Cylinder View (Yanmar Diesel Engine Co. Ltd)*

In the diesel engine, the cycle started from the piston is at bottom dead center and both valves are closed at the beginning of the compression process. Then the air is compressed adiabatically which means the compression is done without heat transfer to or from the environment when the piston is moving upwards. The volume will be reduced but both pressure and temperature will rise. When the piston is about to reach top dead center, the fuel is injected and started to ignite. After the ignition has started, the piston begins to move downwards. In this process, the pressure remains constant but both volume and temperature rise as a result of combustion process. When fuel injection and combustion has completed, the hot gas expands and work is done on the engine. The volume of

gas rises but both pressure and temperature started to fall at this expansion phase. At the end, the exhaust valve opens and the pressure inside the cylinder falls. Then the cycle returns to the first step for gaining a continuous work. (1; 2)

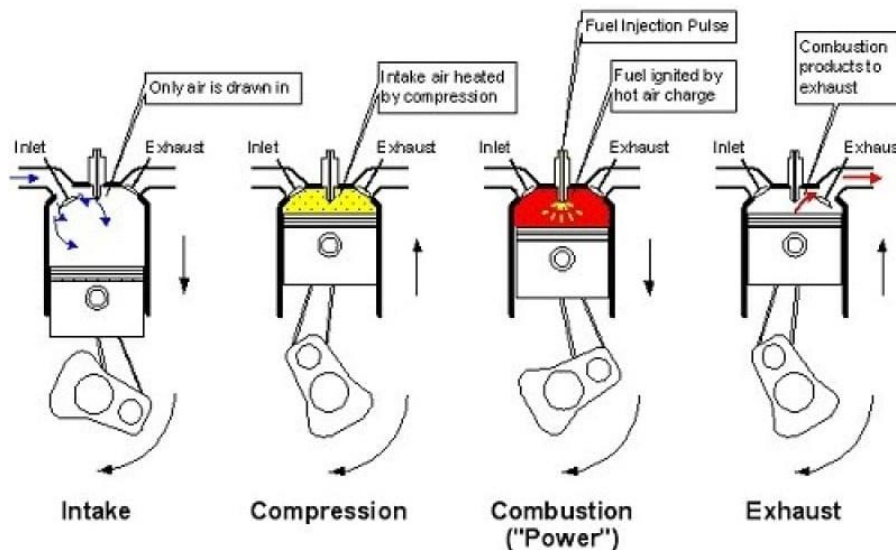


Figure 3. Diesel Engine Combustion Process (Google Images)

### 2.3. Energy Balance Theory (3)

"Energy balance for a direct injection diesel engine shows that about one-third of fuel energy input is lost to environment through heat transfer, another third is wasted as exhaust heat and only one-third is available as shaft work" (Sharma and Jindal 1989). The whole model of this thesis is based on energy balance theory. This theory requires an understanding of how the energy from the fuel that is injected to the engine will produce power for the engine. More precisely, the energy enters the engine in the form of fuel injected and will be used to produce power while some energy will be lost as heat due to friction, cooling water, exhaust, and other heat transfer process. This heat losses should be decreased so that the engine will have higher efficiency. Therefore, it is important to know the theory behind these heat losses.

According to the literature, there are some formula that is used to determine the energy balance inside the diesel engine. Some of the equations are regarding the input energy that is given to the engine, brake power output, etc. Here are some of the examples of the equation formula that is explained in the literature.

$$\dot{Q}_{in} = \dot{m}_f \cdot LHV$$

The formula above explain that the  $\dot{Q}_{in}$  represents the input of energy to the engine is equals to the fuel mass flow ( $\dot{m}_f$ ) times the energy content inside the fuel (LHV).

$$P_b = \tau_b \omega$$

The formula above shows that the brake power output ( $P_b$ ) is equal to the brake torque ( $\tau_b$ ) times the angular velocity of the crankshaft ( $\omega$ ).

The formulas above are reference for the formula that is used in this thesis. For this thesis, the losses are not calculated but it is based on assumptions. So there will be variables of constants that will represent the losses of this engine model. Further analysis of the losses are done in later chapter.

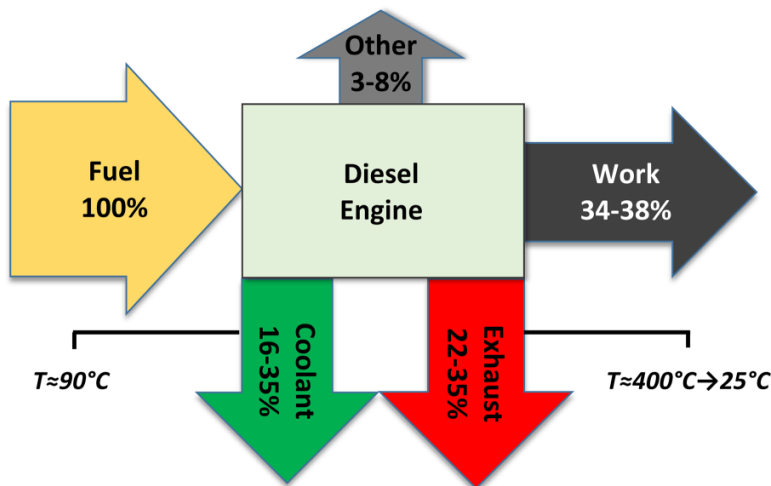


Figure 4. Example of Energy Balance Diagram (Journal of Energy Resources Technology | Volume 139 | Issue 6 | research-article)

## 2.4. Fuel Injection

Fuel injection in diesel engine has task to atomize the fuel and forced it into the engine through a nozzle. The camshaft controls the opening of the nozzle by lifting the pin valve.

### 2.4.1. Direct Injection

In diesel engine, fuel is injected into the combustion chamber directly. The injection aim onto the head of piston when it's about to reach top dead center. The direct injection has high risk due to the injectors will be exposed to both high heat and high pressure. The result is material used for direct injector has high cost due to its high resistance on heat and pressure. The precision is needed to ensure the ignition process as the absence of ignition spark. (2)

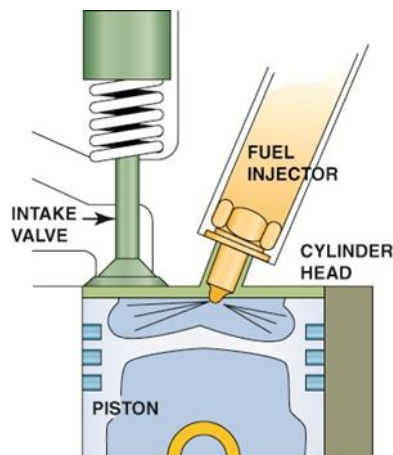


Figure 5. Direct Injection Diagram (Diesel Engine Operation, <http://slideplayer.com/slide/7425299/>)

### 2.4.2. Indirect Injection

The indirect injection system in diesel engine delivers fuel into a small chamber called a swirl chamber or pre-combustion chamber which is connected to the cylinder by a narrow air passage. The swirl chamber



is used to create an increase in fluid motion to perform a better fuel and air mixing. This result is a diesel engine with smoother and quieter condition when running. Because of the presence of swirl chamber, pressure in injector can be lower. Most IDI systems use a single orifice injector. Mostly, indirect injection engines are more difficult to start and require glow plugs to help the combustion process. In addition the indirect injection has lower efficiency than the direct injection due to increase in heat loss. (2)

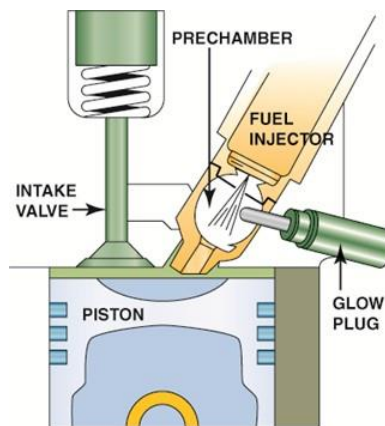


Figure 6. Indirect Injection Diagram (Diesel Engine Operation, <http://slideplayer.com/slide/7425299/>)

#### **2.4.3. Common Rail Direct Injection**

In a common rail system, the common header or the accumulator store fuel coming from the fuel tank then the fuel is sent to the injectors. The header is set to maintain a high pressure. It can also return the excess fuel to the fuel tank. The nozzle sprayed the fuel by the help of needle valve operated with a solenoid. The injection occurred when the solenoid is activated and lifts the needle valve allowing the high pressure of fuel from the header comes out to the combustion chamber. In other hand, the spring pushes the needle valve into the nozzle passage and blocks the path for fuel entering the cylinder. Those happened when the

solenoid is not activated. The overflow of the fuel will go back to the reservoir. Then it will go through the whole process again. (2)

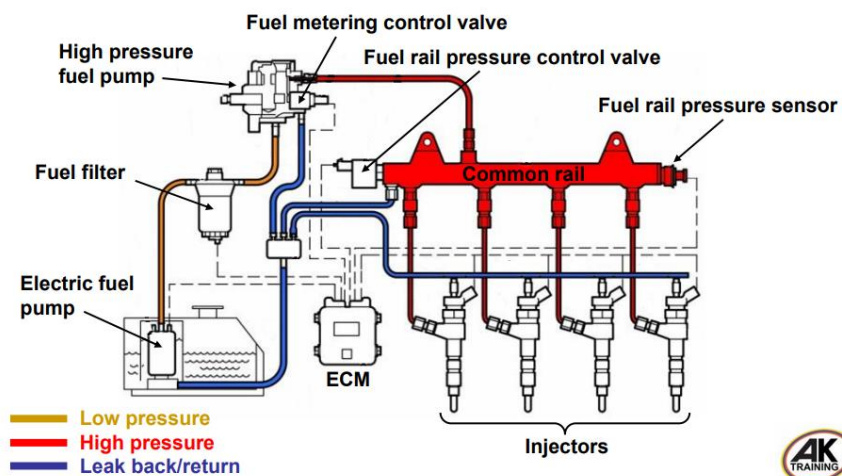


Figure 7. Common Rail Injection Diagram (Common Rail Diesel Fuel System, Tony Kitchen, AK Training)

## 2.5. Engine Efficiency

The efficiency of engine is a result of a ratio of the useful work done to the heat provided. This means the friction and other losses reduce the work done by combustion process. The efficiency of diesel engine mostly depends on the expansion ratio. The work can be extracted from combustion process is proportional to the difference between the initial pressure and the ending pressure during the diesel cycle. Therefore, the bigger the initial pressure can increase the work extracted. (1)

Friction can reduce the efficiency of diesel engine. Diesel engine has friction that produced by many moving parts. There are friction forces remain constant when applied load is constant. There are also other friction losses increase as engine speed increases, for example piston side forces and connecting bearing forces. Only few friction forces that decrease at higher speed,

one of them is the friction force on the camshaft's lobes used to operate the inlet and outlet valves. In addition, an operating diesel engine has another kind of loss called pumping losses. It is defined as a work required to move air into and out of the combustion chamber. This pumping loss is low at low speed, but it will increase as the square of the speed.

Air is important and also needed to perform combustion process. If there is not enough oxygen for combustion, the incomplete combustion will occur and less energy produced. A high fuel to air ratio will produce more unburnt hydrocarbon that affect the engine efficiency.

Some pollutants, for example unburnt hydrocarbon and nitrogen oxide, can be created at high combustion temperature. This can affect the engine efficiency because the energy is being extracted to creating the pollutant instead of for doing work. Somehow it was handled by cooling the air intake to get denser air for combustion process. The engine will produce more power and less amount of nitrogen oxide produced. However, the amount of unburnt hydrocarbon will also increase as the engine produce more power. (1)

## **2.6. MATLAB/Simulink**

To model the engine, the use of software is necessary. The software that is going to be used is Simulink. This program is developed by MathWorks and is a graphical programming program for modeling, simulation and analyzing. The main interface is a graphical block tool and a custom set of blocks that is available in the library. It is based on MATLAB environment, such as the mathematical model of calculation but in a graphical method. Other than mathematical modelling, Simulink can also incorporate MATLAB algorithms into models, which will be beneficial later for further analysis. (4)

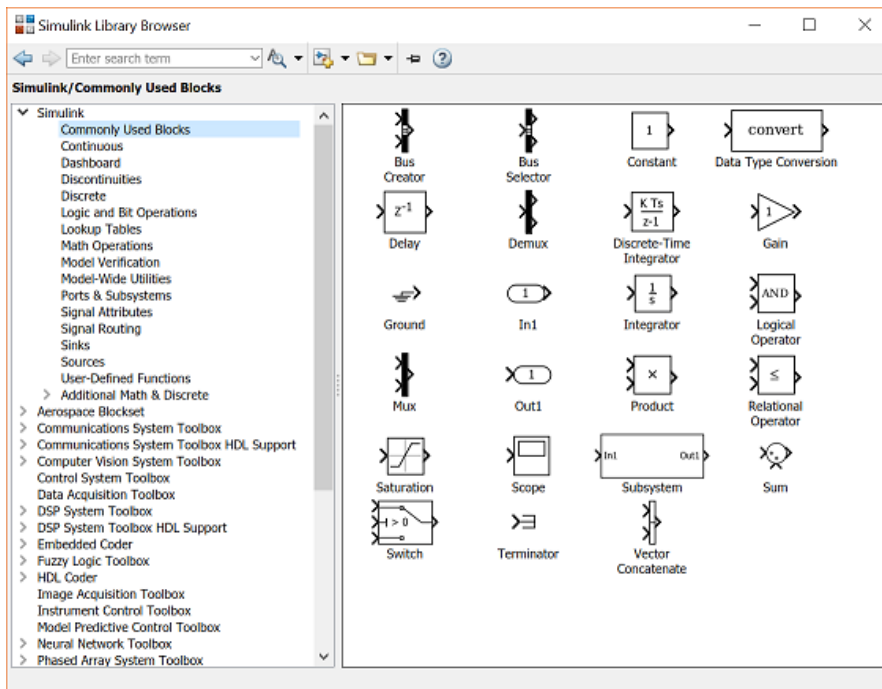


Figure 8. Simulink Library Browser (MATLAB/Simulink)

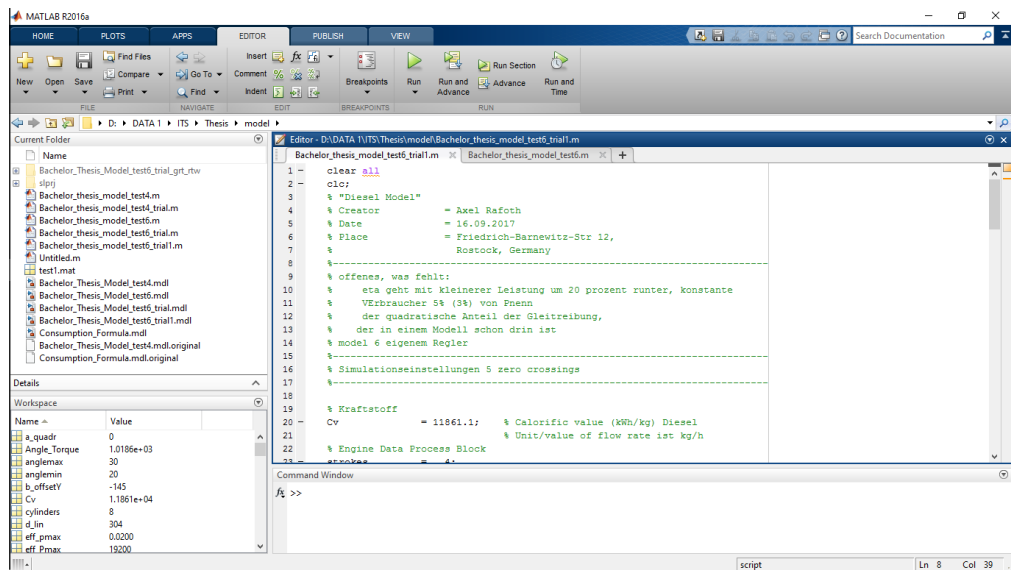


Figure 9. MATLAB Environment (MATLAB/Simulink)

Simulink supports system level design, simulation, automatic code generation, testing and analysis of systems. Simulink is capable of systematic

verification and validation of models through modelling style checking, requirements checking and model analysis itself.

The first step for using Simulink is by modelling the algorithms and physical system using blocks of diagrams. This model can be both linear and nonlinear systems. Factors such as friction, gear slip can also be modelled. A library which have predefined blocks will help in building the model. The blocks are connected in a way that the signal lines can establish mathematical relationships between system components. Refinement of the model appearance or adding masks can customize how the users interact with the model. A group of blocks can be organized into subsystems, which will enable a discrete build of components that reflect real-life system. Simulation of the system can be done after that.

### **2.6.1. Modeling**

As explained briefly in the passage above, modeling in Simulink are basically connecting a diagram of a dynamic system graphically using blocks and signal lines. A block within a diagram defines a dynamic system in itself. Collectively the blocks and lines in a block diagram describe an overall dynamic system.

In general, block and lines can be used to describe many “models of computation”. One example would be a flow chart. A flow chart consists of blocks and lines, but it cannot describe general dynamic systems using flow chart semantics. (5)

The Simulink Library Browser is the library where all the blocks that are used in modelling can be found. These blocks include Continuous and discrete dynamics blocks, such as Integration, Transfer functions, Transport Delay, etc. Other blocks are Math blocks such as, Sum,

Product, Add, etc. Then there is sources block which consists of Ramp, Random generator, Constant, Step, Sine Wave Generator, etc. Lastly, there is the sink block which consists of displays or graphic displays so that the simulation can be seen into numbers, graphics or other values depending on the sink used.

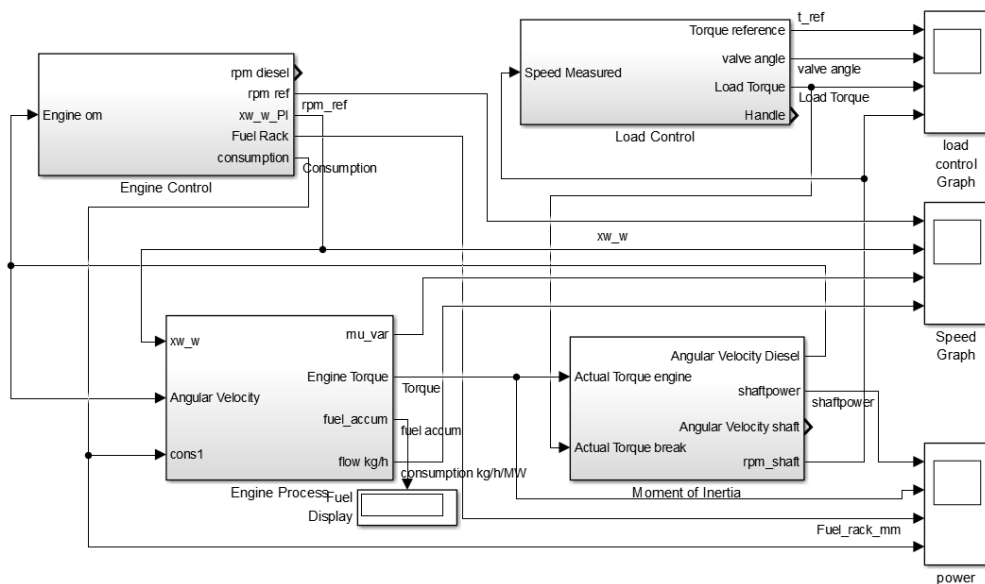


Figure 10. Engine Model for Simulink (Personal Documentation)

The model for this thesis are designed for an engine that is basically using only the energy transfer theories. Inputs of these blocks can be determined by typing the value directly to the block properties, or it can be connected to an .m file which is a file that contains strings of commands or values in MATLAB. These commands or parameters are displayed in the editor panel inside MATLAB. This .m file is useful because the values of the blocks can be changed easily through the .m file. Another reason to input the data in the .m file is so that the monitoring of the values can be done easily, because there will be a display for these values inside the workspace display.

### **2.6.2. Simulation**

Simulation of the model refers to the process of computing the whole calculation or formula that the model is designed and run it in a certain span of time depending on the input time. This process use inputs from the model that is open. Firstly, the program engine invokes the model compiler. This converts the model into an executable form, a process called compilation. Then for the next phase, Simulink allocates memory needed for working areas such as signals, states and run-time parameters. This step will allocate and initializes memory for data structures that store information for each block. Then the simulation enters the simulation loop phase. This phase computes the states and outputs of the system at intervals from the simulation start time to the finish time. This can be done by using the information provided by the model. The successive time points at which the states and outputs are called time steps. The length between time steps are called step size. (5)

This whole process will result in a display or graph depending on the type of sink used. Then these outputs can be analyzed for further research. For this thesis, the results are divided into three main outputs, which are the speed, power and or torque, and consumption. These graph can produce data logs that can be exported into an excel sheet. This way a comparison can be done with another set of data logs.

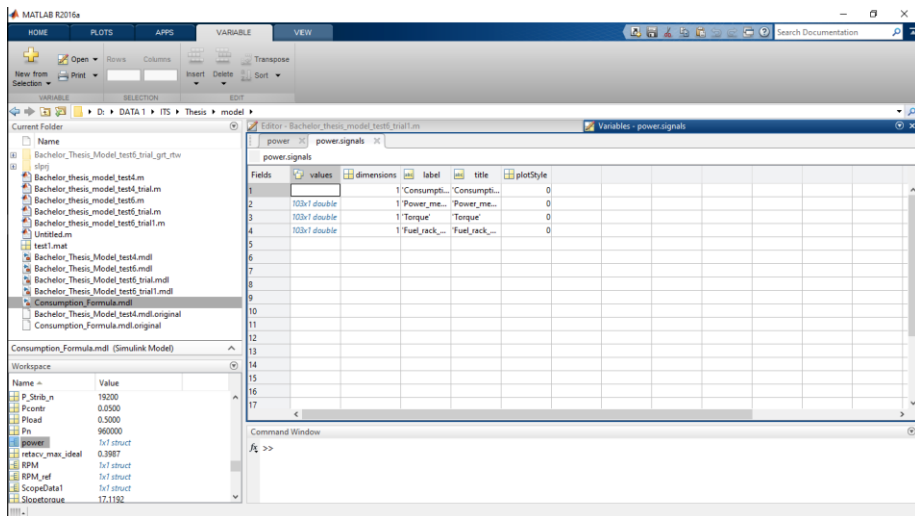


Figure 11. Data Logs (Personal Documentation)

The start of the simulation is by clicking the run button in the Simulink window or in the graph/display window. This will command the Simulink to run the process that is explained in the passage before. A setting for how long the system will run or how many data to be produced can be done. The time for the system to run can be changed in the Simulink window just beside the run button. To change the amount of data to be produced in that period of time, the setting for the display block should be changed.

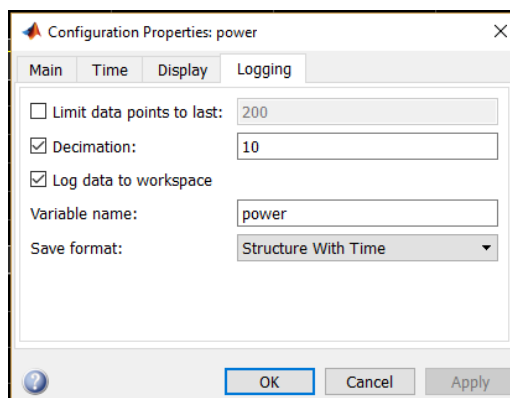


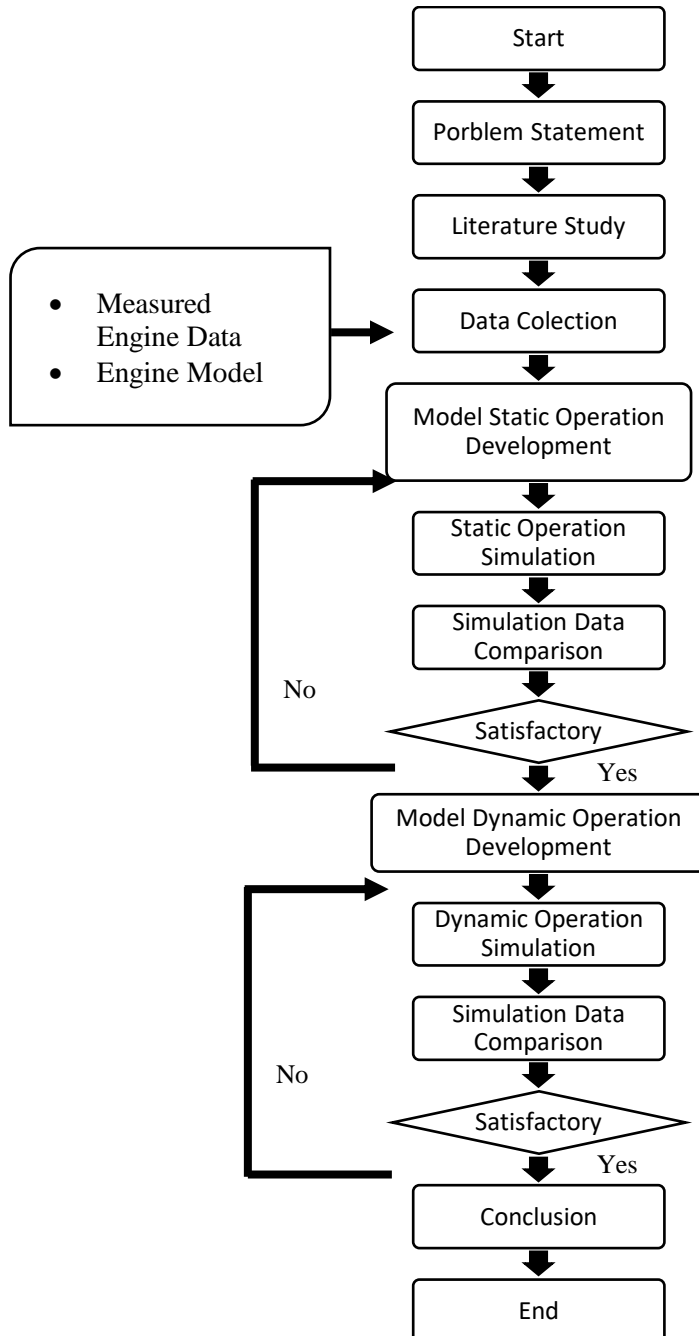
Figure 12. Data Logs Setting (Personal Documentation)



## CHAPTER III

### METHODOLOGY

#### 3.1. METHODOLOGY FLOW CHART



### **3.2. Problem Statement**

The first stage for this report is to identify the problem regarding this paper. The problem occurs because the nature of ship operation gives variables that can be modified so that the ship operation can be more efficient. One of the option to increase the operation efficiency is by increasing the engine efficiency itself. The engine efficiency is usually determined by the difference of fuel consumed by the engine and the power that it creates. These fuel will naturally be used not only to generate power, but also generate losses such as friction, heat, and other losses regarding the engine operation.

Developments in maritime industry nowadays usually are based on designs of the engine and simulation of the engine using software assistance. This thesis will focus on the design of an engine model, which then will be used for simulation. The basic characteristics of a model of an engine is not the same as the real engine. The process of the engine is quite different because there are no natural law of physics that will help the model to run as similar to the real engine. This is because a model needs artificial physics formula that to be added by the user.

To understand the model design, one must understand the process of a diesel engine and all its supporting parameters. The engine process itself have been explained in many literatures, as well as the parameters for those process. For example, the engine combustion process will need an understanding of the parameters of the temperature, pressure, mass flow.

### **3.3. Literature Study**

On this stage, some books and journals are used to provide sufficient data for this research. The aim for this stage is to explain the depth of review,

summarizing the basic theory, general and specific reference, and obtaining various other supporting information related to this research. This literature study is conducted on generally diesel engine process and parameters that will be used for calculation. Then there is also theories for energy balance and thermodynamics. This is important due to the characteristics of the model itself, which is that the model is designed based on the energy balance theories. Theories such as MATLAB/Simulink tutorials are also important for this research because this research uses that software for supporting the calculation and diagram plotting. The aim for this stage is to obtain basic theories, formulas that are useful for the calculations, and methods that can be used in solving the problems.

### **3.4. Data Collection**

There are some data that must be collected to help in this research. These data are collected through some methods that are commonly used such as reference collection, real-life measurements, or laboratory measurements. The data that are used consists of:

1. Measured Engine Data, which is the data of each operation points with the corresponding time and values. These values are mainly for comparison so that the model can be assessed to be similar or not.
2. Engine Model, is the most important thing to be collected, because the creation of an engine model will require a lot of time and for this thesis, therefore, the use of an existing model will help with the whole process.

### **3.5. Model Static Operation Development**

The model needs to be developed to create a more similar results to measured data. This stage will develop the model to be similar in the static operating points. This way, the model will be stable enough to be simulated under dynamic operation. There are some ways to create a suitable model for this matter. Firstly, there should be a change in speed and consumption calculation. This is why there will be a new consumption formula added. This formula is hoped to be able to create a more similar power and torque results. Other than the consumption formula, the losses of the model will also be changed. The reason to change the losses variables is because the model characteristics of the power calculation. The power calculation are basically the fuel consumed multiplied by the calorific value and then it will be subtracted by the losses of the engine model. This way, the losses will affect the power generated directly. The controller will not be modified thoroughly, because it will not create much difference in the result due to the constant value of the result.

### **3.6. Static Operation Simulation and Comparison**

After the run, there will be results as graphs, which will be used for the comparison with the measured data. The measured data that were collected are in the shape of a graph too. But to compare it correctly, the measured data should be first converted to an excel sheet. Therefore the value are clear and easy to analyze. Then the simulation data are also logged from Simulink to create a sheet for the comparison. After all the sheet are collected, a graph for a certain value and operating points can be created. This graph will show the difference of the results. Based on the results, a change of parameters in the model should be done accordingly. Then another comparison is done until the result are satisfactory.

### **3.7. Model Dynamic Operation Development**

After the static operating points are developed, the model will be stable enough to have some changes in the inputs that resembles the dynamic process of an engine. This dynamic process includes a sudden increase of engine speed, or a sudden drop of torque, etc. These two parameters are important parameters because it will affect the power and consumption greatly. The basic formula for basically every process in the model are based on the speed of the engine and the load of the engine or the torque reference.

To change the graph or the behavior of the engine to be similar to that the measured data, some values of inputs in the parameters should be changed. These parameters are the  $K_p$  and  $K_i$  in the controller block. These PI controller are controlling both the engine and the load reference. For the engine controller, the system will regulate the fuel rack position, therefore the consumption and the power will directly affected. Then the torque or load reference controller will control the load reference output. This will affect the angular velocity that will affect the speed difference for the speed controller input. This means that all the controller are connected and affecting one another in a loop system.

Then another change is done in the input of the engine speed. This input have some change based on the measured data. According to the data, there will be a sudden drop of speed and then after a couple of seconds, the speed will continue to increase until the operating point. This matter is solved by adding two separate block that will affect the speed. The first speed change block will decrease the speed, and the second will increase the speed. Both are done in a specific time and specific value of gains. This matter will be explained in later chapter which discusses the dynamic operation points.

### **3.8. Dynamic Operation Simulation and Comparison**

The simulation of the engine is done by pressing the run button in the Simulink model or the display window. This will run the model accordingly to the parameters that are set before. A more detailed explanation of the process of the simulation are explained in the chapter before regarding the MATLAB/Simulink theories.

After the run, there will be results as graphs, which will be used for the comparison with the measured data. The measured data that were collected are in the shape of a graph too. But to compare it correctly, the measured data should be first converted to an excel sheet. Therefore the value are clear and easy to analyze. Then the simulation data are also logged from Simulink to create a sheet for the comparison. After all the sheet are collected, a graph for a certain value and operating points can be created.

It is exactly the same procedure as the simulation and comparison in the static operation points. The difference will be the action that will be taken after the simulation is done and there are difference in the results. The first thing to do is to check the controller values. These values, the  $K_p$  and  $K_i$ , should be changed accordingly to achieve a similar results to that of the measured data. The explanation of the controller modification can be found in later chapter regarding dynamic operations.



## **CHAPTER IV**

### **DATA ANALYSIS**

#### **4.1. Engine Model**

The engine model is designed by Prof. Dr.-Ing. Axel Rafoth. This engine model is based on energy balance theory. There are two major parts in this model. One is the parameters file which is compiled into an .m file from Matlab. This way, the calculation of inputs in the model can be done in a separate file. Then there is .mdl file which contain the model itself. Every Simulink model is based on blocks and connections which is explained in previous chapter. The model combines the use of subsystems and loops to create a similar operation or process to that a diesel engine.

The model itself consists of blocks and connections that are arranged so a similar system of an engine can be made. The main blocks are:

- a. Engine control block
- b. Engine process block
- c. Load control block
- d. Inertia block

This sub-chapter will explain each block that is inside the model and what these block will represent. Parameters that are used inside the blocks will be explained in later chapter about parameters in the .m file.

##### **4.1.1. Engine Control Block**

The first block is the engine control block. Inside the block, there are set of subsystems and connections that is controlling the



speed of the engine, the consumption of the engine and the fuel rack position calculation.

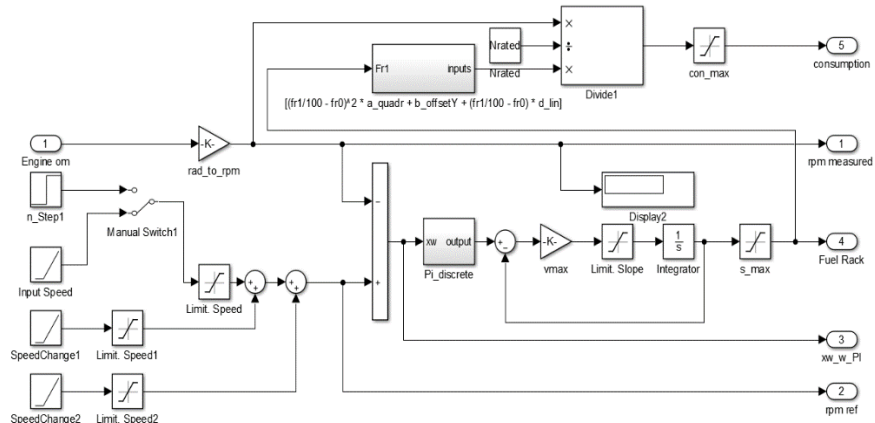


Figure 13. Engine Control Block (personal Documentation)

As shown in Figure 13, it shows that there are constant inputs for the speed or in this case the throttle handle itself.

From the input speed block in the left corner of the figure, the speed of the engine is controlled. Then it goes to the controller for the fuel rack. All the ramps in the left section is an array of ramps that is used to generate a similar situation of dynamic operation. The main input is the ramp called the *Input Speed* block. The two other ramp, which is called the *SpeedChange1/2* are used to add the change of speed during dynamic operations. If the operation is in static operations, then the two ramps can be used by changing the value of the input into zero. This will create no change in the initial input of the speed by the top ramp.

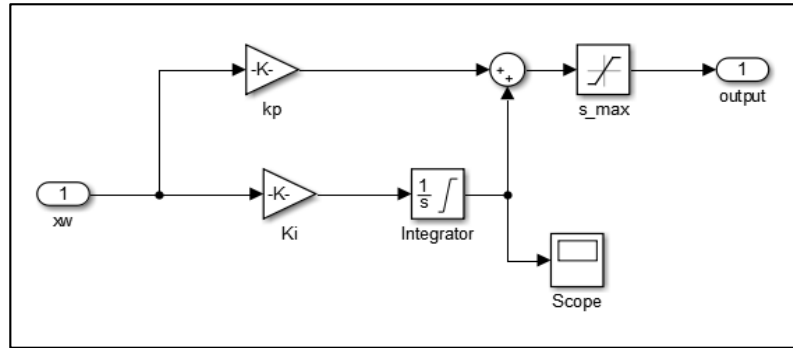


Figure 14. PI discrete Block or the Controller Block (personal Documentation)

This controller's input is from the .m file which will go to the  $K_i$  and  $K_p$ .

By changing this values, the injection or fuel rack results will be more similar to the real measured data. Then there is another input in the left which is the engine omega or angular velocity of the engine in the crankshaft. This value is important because it will also be used in the consumption formula. The consumption formula is located in the top section of the figure. The whole blocks and connection of the formula is a translation from the mathematical model. The mathematical formula for the consumption is

$$Consumption = \frac{N_{input}}{N_{rated}} \cdot [b_{offsetY} + \left(\frac{fr1}{100} - fr0\right) * d_{lin}]$$

And then there is a subsystem which is the bracketed section in the formula above. This block is basically a subsystem to make the display simpler without changing the formula as a whole.

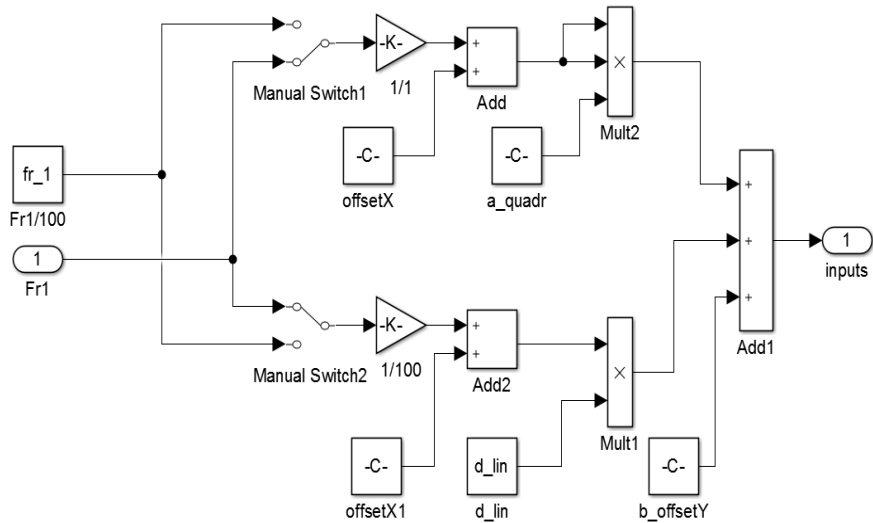


Figure 15. The section from the formula (personal Documentation)

Then after the consumption is calculated, it will be used in other calculations such as the engine process. The output of this engine control block are measured RPM, RPM reference, PI controller, Fuel Rack Position, and Consumption. These results will be used in another block and/or shown in the display.

#### 4.1.2. Load Control Block

The second block is the load control block. Inside the block, there are set of subsystems and connections which are controlling the load of the engine, the torque reference and the inputs of torque reference.

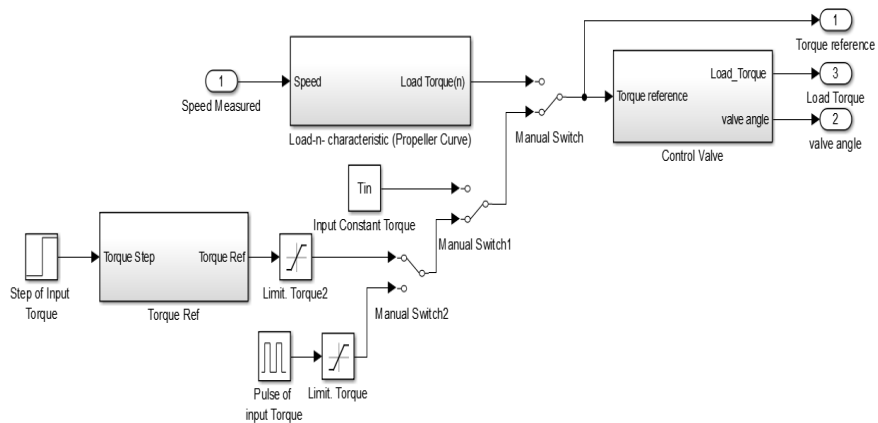


Figure 16. Load Control Block (personal Documentation)

As shown in Figure 16, there are 3 subsystems in this block. There are also these manual switch which can be operated manually to change the connections between the blocks. There is a constant value of  $T_{in}$  which is very useful for low speed operations. Because this model have a characteristics to calculate the torque based on the gain of the speed. Which means that if the operating points is in the low end of the speed curve, the torque will be less than expected. Therefore a constant input of torque is a more suited option for this matter. If there is sufficient torque, then the load torque will be sufficient so that the power and the consumption match the real engine. Although there will still be minor differences in numbers.

The first subsystem, which is the Load Characteristic Block, will be used to create a propeller curve, which is dependent to the speed of the engine. This subsystem will be useful for static operating points where there are no change after a certain speed is achieved. This certain block is the reason why there is a need for a constant input of torque instead of a speed-dependent torque block. This speed-dependent torque is called engine rotational torque. This torque is what cause the crankshaft to turn. The basic theory behind this is that

the torque is equals to force multiplied by the radius or length of the arm. This force is based on mass multiplied by acceleration. So if the acceleration is high, the torque will also increase.

From Figure 17, it shows that the load torque is mainly affected by the speed inputs. Therefore if the speed input is almost the same as the  $Nmin$ , then there will be less acceleration. Then the block will calculate the load torque according to this small value. This is a problem that is still under evaluation and will be done in the future research. The formula for the Figure 17 is,

$$Load\ Torque = \left( \frac{\left( \left( \omega \cdot \frac{60}{2} / \pi \right) - Nmin \right)}{(Nrated - Nmin)} \right)^2 \cdot Slope\ Torque$$

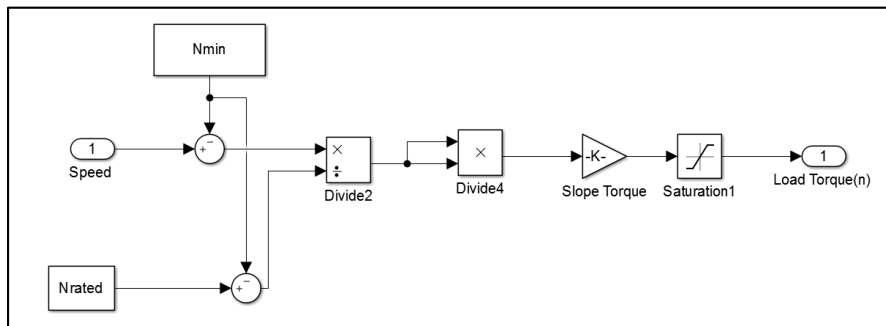


Figure 17. Load Characteristic Block (personal Documentation)

The next subsystem is the torque reference which controls the torque gain for a certain amount of time. This subsystem consists of a step input, a ramp function and a constant input of initial torque. This initial torque are calculated in the .m file. The explanation of the torque reference calculation can be found in passage 4.2.

This block is mainly used in the dynamic operating points, because it can change the torque reference according to the desired

amount in a certain span of time. This is the aim of the dynamic operation.

As shown in Figure 18, the input of this block is the Torque Step, which is a step function that have a certain value for time and a certain value for gains. This value then is transferred to the ramp function. This is to create a similar results to that of a person operating the throttle of the engine, or a person operating a machinery which will create an increase of torque overtime.

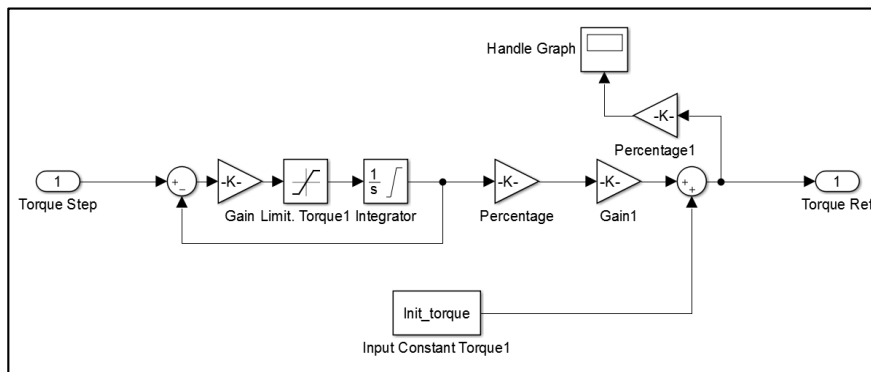


Figure 18. Torque Reference Block (personal Documentation)

The control valve block is the third subsystem in this block. This subsystem consists of the controller of the torque itself. Within this subsystem, there are a PI controller, ramp function, and valve angle output. The PI controller is the same composition as the controller from the engine controller block. The difference is the value of input in the controller. For this block, the inputs are *Iload* and *Pload*. These inputs can be found in the .m file. Figure 19 shows the control valve block. This block consists of a calculation for the load torque. The load torque value will be used in another block for calculating the angular velocity of the engine. More explanation of the use of the load torque can be found in the chapter about the angular velocity block.

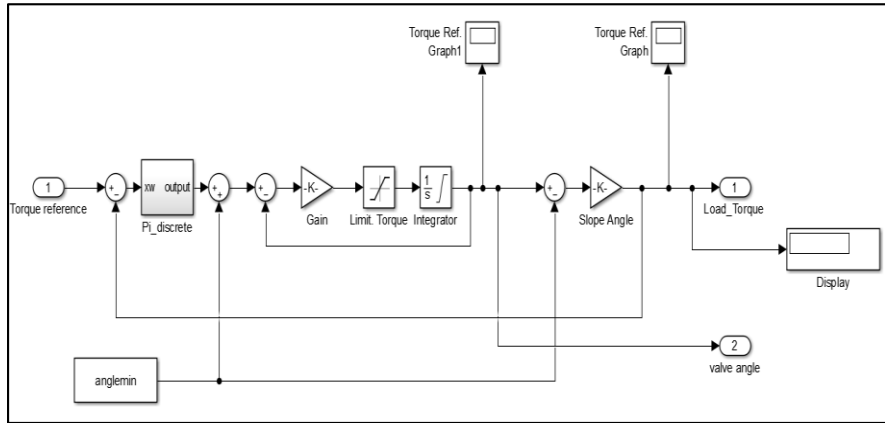


Figure 19. Load Controller Block (personal Documentation)

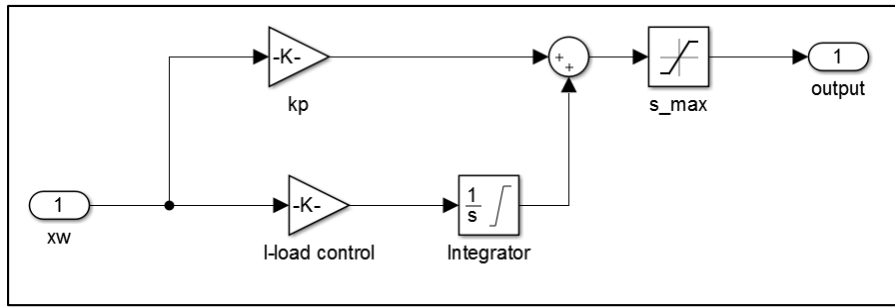


Figure 20. PI Controller Block (personal Documentation)

#### 4.1.3. Engine Process Block

The next block is the engine process block. Inside the block, there are set of subsystems and connections that is controlling process of the engine itself. These process includes the losses calculation, the burning process, and the efficiency calculation, and the engine torque itself. These calculations mainly have inputs from other blocks which have been explained before. Inputs for the *etacv\_max* constant block in the left corner is calculated in the .m file.

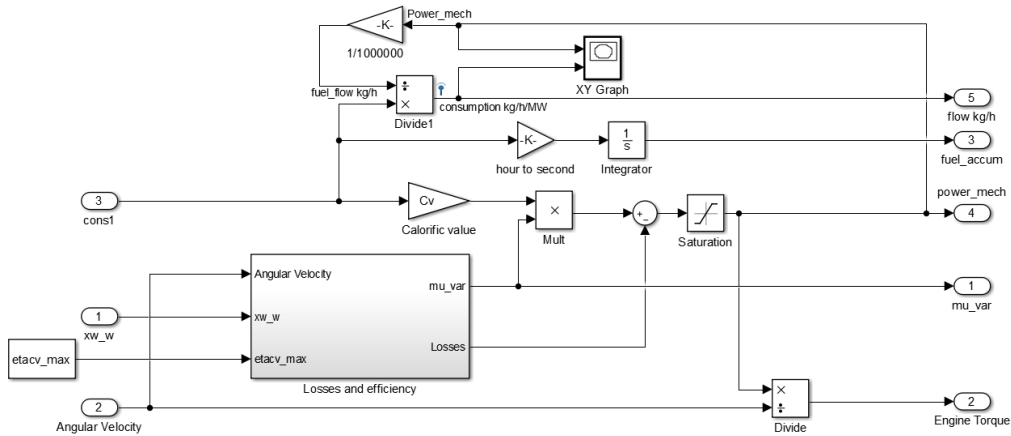


Figure 21. Engine Process Block (personal Documentation)

Figure 21 shows the connections that is arranged in the block. For the power of the engine, as explained in previous passage, the calculation is by using the consumption value and the efficiency, then it will be subtracted by the losses. It is a simple logic of energy balance which is explained in the Chapter II.

The consumption value is from the engine control block. The consumption times the calorific value of the fuel will result in energy for the operation. This energy is used to determine the power. The efficiency times the consumption will result in power. In short, the formula should be,

$$Power\ Overall = (Consumption \times Calorific\ Value) \times Efficiency$$

Then the power of the engine can be calculated. The formula is,

$$Brake\ Power = Power\ Overall - Losses$$

From the brake power, the calculation of the torque can be done. The formula for power in terms of torque is,

$$Power = Torque \times Angular\ Velocity$$



Therefore, the torque can be calculated by using the same formula which is changed to,

$$Torque = \frac{Power}{Angular Velocity}$$

The next important thing in this block is the *Losses and Efficiency* block or subsystem. This subsystem contains the whole calculation for the efficiency and losses. The calculation for the efficiency of the engine can be seen in the figure below. The explanation of each block in the figure can be found in the explanation about the .m file.

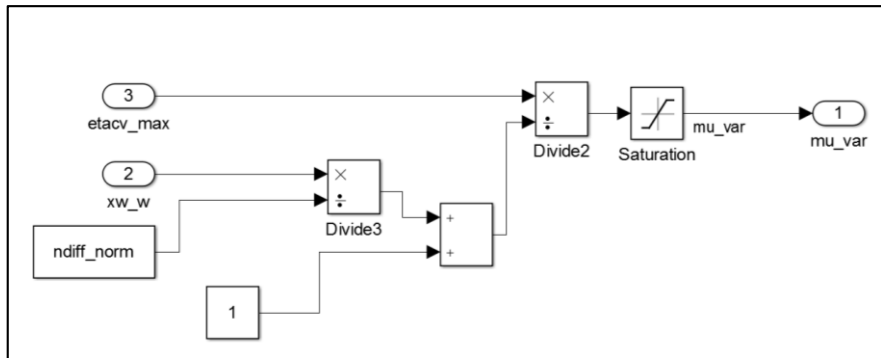


Figure 22. Efficiency Block (personal Documentation)

The losses block is shown in the Figure 23. The first aspect of the losses is the speed dependent losses ( $T_{hangon\_vn}$ ), to get this value, the losses parameter from the .m file should be multiplied by the angular velocity.

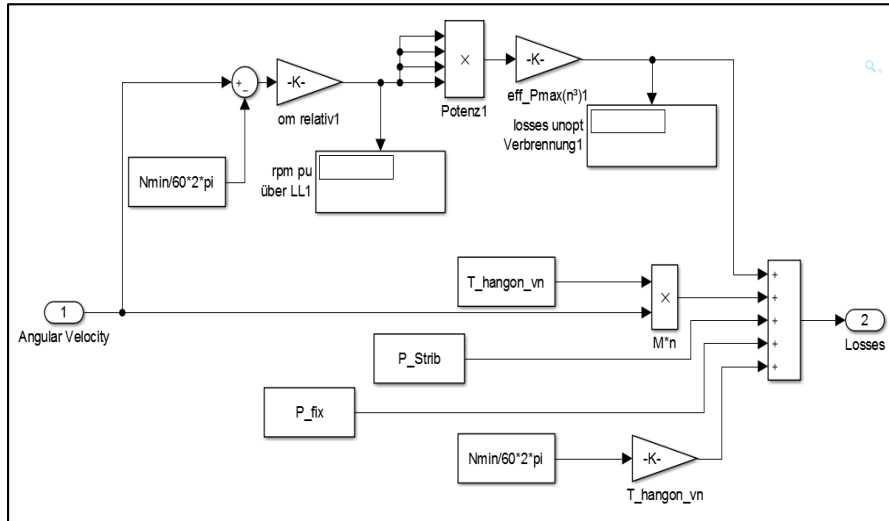


Figure 23. Losses Block (personal Documentation)

Then there is the friction losses ( $P_{Strib}$ ), the fix losses ( $P_{fix}$ ). To add to the whole system, there is another losses to be remembered. To assume that there is some machinery that is crucial to the engine operation such as the pumps for the cooling, fuel pump, etc. These machineries usually will be coupled to the engine itself, therefore another losses of such should be added. The block where the minimal angular velocity is multiplied by the  $T_{hangon\_vn}$  is the losses for this matter. Then there is also losses from bad combustion process. This is explained in the blocks in the top. The angular velocity of the operation will be subtracted by the minimal angular velocity. Then in will be multiplied by the relative angular velocity. This value will be in the power of four before it is multiplied by the variable of the bad combustion. To make it short, the formula is,

$$Unopt\ Combustion = \left( \frac{\omega_{operation}}{\omega_{min}} \cdot \omega_{relative} \right)^4 \cdot C$$

The C in the formula above is a result of the constant for bad combustion multiplied by the rated power.

#### 4.1.4. Moment of Inertia Block

This block controls the angular velocity of the engine, the angular velocity of the shaft and shaft power. The input of this block is the engine torque from the engine process and the torque load from the load controller block. These inputs will be used to calculate the angular velocities and the shaft power.

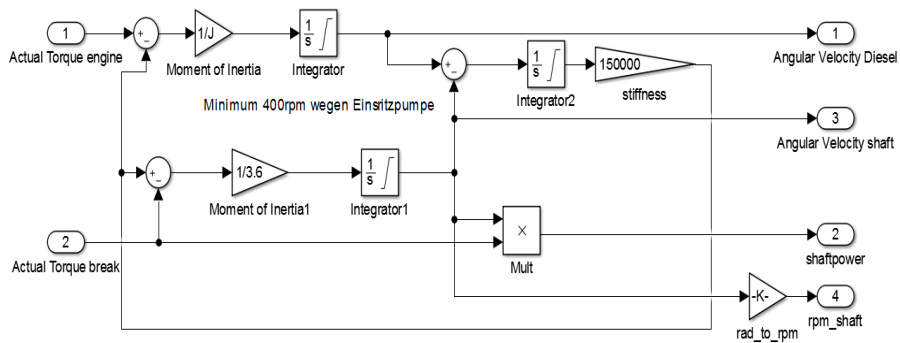


Figure 24. Inertia Block (personal Documentation)

Figure 24 shows the inertia block and its connections. On the left side, there are two inputs which are the actual torque of the engine and the actual torque of the break. This break is an equipment to transfer the torque from the engine crankshaft to the measurement equipment. This is because there is no way to actually measure the torque directly in the crankshaft while the piston is pushing it down. Therefore the system will be using a two-mass configuration. This two-mass system requires another inertia factor so that the system can run as similar as the real engine. The first part is the engine inertia. This is not modified much because the model already uses this in the previous block configuration. There is an

addition of a break inertia block. This block is similar to the diesel inertia block, but the difference is at the inertia of the part itself. For the engine inertia, the value is 45 kg.m<sup>2</sup>, but at the break inertia, the value is 3.6 kg.m<sup>2</sup> (6). Another added part is the stiffness block. This is to represent the elasticity of the coupling that connects the two mass of inertia. This stiffness will be a load input to the engine inertia, but for the break inertia, it will be the source of input. This way, the actual system as a coupling is done. From Figure 24, the shaft power is calculated by multiplying the break torque with the break angular velocity.

#### 4.2. Parameters from .m file

The parameters and values that is used in the model are pre-determined. Therefore if there should be any change, the value can be changed from the .m file. This makes the modification of the model simpler because the input value in the model will not be changed. Only the value of that input will be changed in the .m file.

Those parameters are:

```
% Kraftstoff
Cv          = 11861.1;      % Calorific value (kWh/kg) Diesel
                                % Unit/value of flow rate is kg/h

% Engine Data Process Block
strokes     = 4;
cylinders   = 8;
Pn          = 960000;      % power maximum 6NVD (W)
Nmin        = 485;        % idling Speed of engine (RPM)
Nrated      = 900;        % Speed rated of engine (RPM)
Ninput      = 490;        % input of rpm in specific operating points
```

Thread 4.1. Engine model parameters 1

Thread 4.1 shows the engine data from the model. These parameters are used in the model as inputs so that the whole process will run better. From the data above, the only value that will be changed overtime is the

*Ninput* value which is depending on the operating points that are being analyzed. The rated torque will be calculated based on the rated power of the engine. The formula is as shown in the *Thread 4.1*.

```
% engine losses static (subject to changes for better test results)
p_fix      = 0.04;          % fix losses / additional constant
P_fix      = p_fix*Pn;      % shared constant losses
p_hangon_vn = 0.07;        % Losses that is dependent to engine
speed
T_hangon_vn = (p_hangon_vn*Pn)/(Nrated/60*2*pi); % M const -> P
that is dependent to speed P~n2
p_Strib    = 0.02;          % Friction losses - constant gain
P_Strib    = p_Strib*Pn;    % Friction const
P_Strib_n  = p_Strib_n*Pn;  % M linear*n or P*n2 delta
eff_Pmax   = eff_pmax*Pn;   % high speed potential of efficiency
based on n

% efficiency over all from data optimum point and losses
%etacv_max   = 0.41;        % max. Efficiency of Engine as a
function
etacv_max   = ((Pn*p_opt)+P_fix+P_Strib + (T_hangon_vn *
(Nrated/60*2*pi)))/(Flow_opt); % efficiency formula
etacv_min   = etacv_max*0.60; % min. from etacv_max of burning
process, f(xw)
```

#### Thread 4.2. Engine model parameters 2

*Thread 4.2* shows the engine losses and efficiency formula for the model. These losses value will later be used for determining the load of the engine in the model. To explain in more detail, the losses that are assumed were fix losses, speed-dependent losses, and friction losses. The values of the initial losses are all based on assumption from journals and reference that explains the behavior of a diesel engine. Then these initial losses are used for the actual losses that will be calculated from the formula above. Then from these losses, there will be a process in the model which will generate the overall losses. From that block, the efficiency can be calculated in this .m file. The formula for the efficiency is as shown above. To explain it in a more simple way, the efficiency of the engine is equal to all of the losses added and then will be divided by the optimal flow rate.

```

% Engine Controller Block    % adjusted according measurement
Pcontr                      = 0.45;          % Proportional gain of controller
Icontr                      = 0.2;           % Integral gain of controller
(changed from 0.53 for tests)

% Consumption Block
V_scale=1/900;
a_quad=0;
b_offsetY=-145;
offsetX=0.22;
d_lin=304;
fr_1=91.1; %input of fuel rack position during operating points and
it is from the measurements%

```

#### Thread 4.3. Engine model parameters 3

*Thread 4.3* shows the engine controller block parameter. These value will later be used for determining the controller of the speed and fuel injection process. To do that, the *Pcontr* and *Icontr* value will be changed to create stable operations. Then there is the flow parameters. These parameters contain the fuel rack parameters that will be used in the model. Other than that, it will also contain the parameters for the consumption calculation of the engine model. The formula for the consumption itself is explained in previous chapter about blocks and connections.

```

% Load Control Block
Pload                      = 1.21;          %Proportional gain of PI controller
to load
Iload                      = 1.07;          % Integral of PI controller to load

Tmax                      = 2339; % Torque maximum (200%) (Changed from
2*Trated for tests)
Tmin                      = 100;           % Torque minimum (Nm)
Tin                      = 2339;          % 8030 2000Nm idle Brake Torque input
% Inertia Block
J                          = 45;           % Moment inertia for crankshaft
(kgm^2)
J_break                   = 3.6;          % Moment inertia for break (kgm^2)

```

#### Thread 4.4. Engine model parameters 4

*Thread 4.4* shows the load controller block parameter and the inertia block parameter. These value will later be used for determining the controller

of the load and torque of the model. The *Pload* and *Iload* will be changed to create a more stable operations. For the torque itself, it is calculated in the model, but the limitations are pre-determined in this .m file. The *Tmax* value and *Tin* value will be changed according to the operating points that are being analyzed. The inertia block is used in the angular velocity block which will determine the angular speed of the engine.

```
% Handle
operatingT=(Tin/Trated)*100; %operating torque percentage
Tinit=Init_torque/Trated; %initial torque percentage
input_torque=operatingT-(Tinit*100); %torque value which will be
added to the initial torque to achieve operating torque
```

#### Thread 4.5. Engine model parameters 5

*Thread 4.5* shows the torque reference block. This block controls the gain of the torque during the operations. There are some key parameters to be calculated. Those are the initial torque, operating torque, and the overall input of torque to fulfill the operating torque. The initial torque is calculated based on the initial power that is measured. This way, there will always be torque even while idling operation. This is to eliminate excessive gain in the gain controller. The operating torque is the whole torque used in a certain operating points. This is a result of the initial torque added by the input torque. The input torque itself is calculated by subtracting the operating torque with the initial torque. For the leftover torque, it is the torque that is calculated from all the torque other than the initial torque, but it is based on the rated torque, which is based on the rated power, not the initial power.

Some values in the .m file is changed based on the comparison with the measured data which is obtained by running the real engine in the laboratory, such as power, torque, speed, etc.

### **4.3. Model Development**

The model for this thesis is running as a model, but it is still not similar to a real engine. In this case, the engine that is used for comparison is the engine in the laboratory of the University. To create a similar running process from the model, some adjustments must be made.

#### **4.3.1. Structural Change**

The first model is different from the model that is currently used in this thesis. It has been modified by changing some blocks and even adding other blocks to create a more similar results from the simulation. The first change that was made was changing the way the losses of the engine to be calculated. In the first model, the losses for the incomplete combustion are included in the losses system, but this can be simplified by separating the incomplete combustion losses to be another type of losses. Therefore the accuracy of the calculation is increased. And then the whole incomplete combustion is not affecting the calculation of the efficiency anymore, but it is added to the total losses, which will be used to subtract the power to get the real usable power.



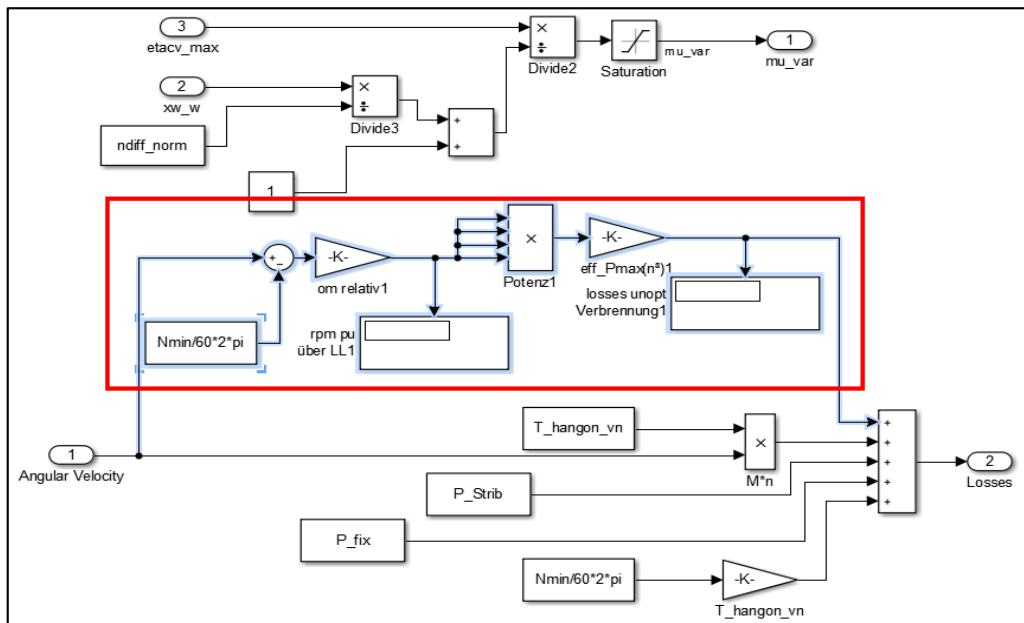


Figure 25. Incomplete Combustion Losses (personal Documentation)

Figure 25 shows the highlighted section as the incomplete combustion losses. This block was originally connected to the efficiency calculation block, which is now above the losses block.

Then the engine control block also gets a modification. First there is a problem with the fuel rack position being too low for the whole process. On the first model, the consumption is calculated in the engine process block, which gets its input by the flow rate or in this case the fuel rack for the model. But this is not exactly true, because the flow rate is not equivalent to the fuel rack position. This problem is solved by adding the new formula to the model. And this formula is the calculation of the fuel consumption itself. In this formula, the fuel rack are used to calculate the fuel consumption, therefore the value of the power and torque are more similar to that of a real running engine. This consumption formula is explained in the chapter above regarding the engine control block.

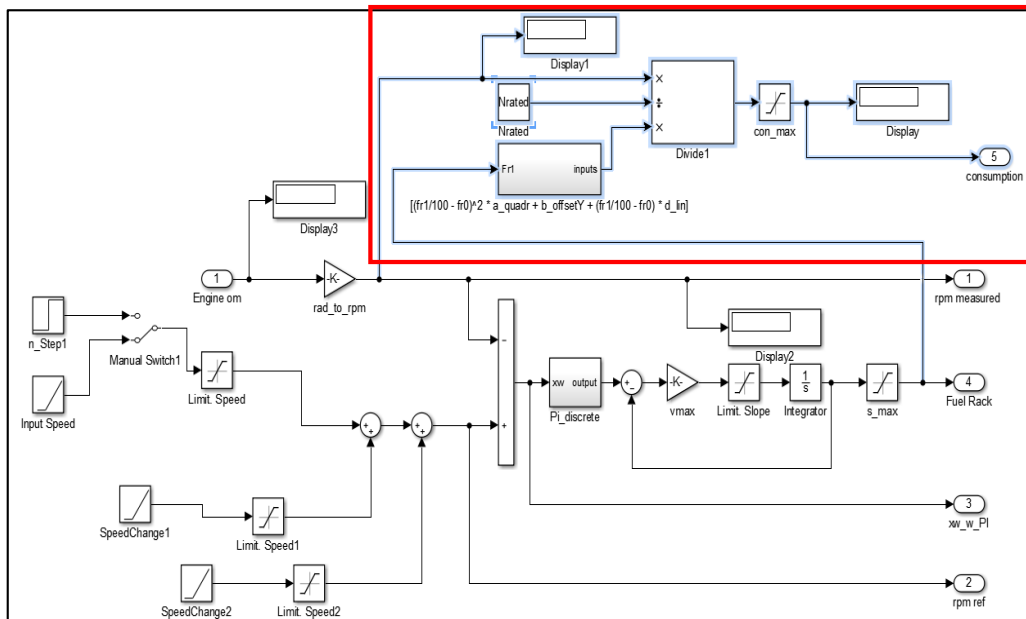


Figure 26. Fuel Consumption Block (personal Documentation)

Figure 26 shows the highlighted area as the Fuel Consumption Calculation block. This is a new addition to the model which will calculate the fuel consumption using the inputs of fuel rack position and engine speed as its primary input. Other inputs are constants which will be controlled by the .m file.

After the engine control block and the losses block is modified, there is another block that is modified. It is the inertia block, which previously use a one-mass system. This block originally is meant to measure the initial torque that the piston give to the crankshaft directly. But in reality, there is no way to measure this value. Instead, there is another system that is coupled with the crankshaft. This system is called the break system. This way the torque can be measured. Therefore the model is modified to use a two-mass system for the inertia block. The whole explanation of this two-mass system is already explained in the previous chapter about blocks and connection.

### 4.3.2. Parameters Change

The model can be modified as it is because there are some trials and errors that have been made. From the first model, a simulation is done and by that simulation result, it is compared to the measured data. From this comparison then the model can be adjusted accordingly. The parameters are also one of the key factors for this process to succeed. Parameters such as RPM input, input torque, losses constant, can be changed accordingly based on the operation points that is being analyzed. This is why for the first step of the model modification, these are the parameters that is changed frequently other than the changing of the structure of the model itself. *Thread 4.6* shows that the highlighted area is the input RPM which will be changed accordingly to the analyzed operating points.

Nmin	= 485;	% idling Speed of engine (RPM)
Nrated	= 900;	% Speed rated of engine (RPM)
N opt	= 830;	% rpm optimal
Ninput	= 490;	% input of rpm in specific operating points

*Thread 4.6. Engine Speed Parameter*

An example of why the parameters need to be changed is the basic behavior of this model. This model is based on the energy balance theory, therefore the power and torque created are related to the losses that is present in the model itself. If the power or torque are not adequate, then the consumption and fuel rack position will also be affected even though the engine speed is already the same as the desired value.

#### a. Static Operation

When analyzing the static operating points, one problem arise when the simulation for low RPM and low load are being done. This

operating points is still in the static stage, so there will be no sudden change of speed, or power, or torque in a certain amount of time. This operating point needs the load to be low while the rpm is also low, which the first model did not produce. Then according to the basic energy balance theory, then to increase the torque, then the losses must be changed, because as the basic thermodynamics, power equals torque multiplied by the angular velocity.

```
% engine losses static (subject to changes for better test results)
p_fix      = 0.04;          % fix losses / additional constant
(changed from 0.01 for tests)
P_fix      = p_fix*Pn;      % shared constant losses
p_hangon_vn = 0.07;        % Losses that is dependant to engine
speed (changed from 0.05 for tests)
T_hangon_vn = (p_hangon_vn*Pn)/(Nrated/60*2*pi); % M const -> P
that is dependent to speed P~n²
p_Strib    = 0.02;          % Friction losses - constant gain
(changed from 0.01 for tests)
P_Strib    = p_Strib*Pn;    % Friction const
```

#### Thread 4.7. Losses Parameters

*Thread 4.7* shows the green colored fonts as notes for further analysis. As explained before, the losses should be changed accordingly to create a similar results as the measured data.

Another parameter that is changed a lot during the static operating points is the parameters for the torque limitations. This limitation is needed when the torque that is generated goes beyond what the measured data shows. Another important parameter is the *T<sub>in</sub>* parameter, which is a constant input of torque. As explained before, the model have a characteristics of calculating the torque based on the difference of engine speed. But this is only for the static operating points. Therefore, when simulating a low rpm and low load operating point, the torque does not reach the desired value.

```

Tmax          = 2339; % Torque maximum (200%) (changed from
2*Trated for tests)
Tmin          = 100;   % Torque minimum (Nm)
Tin           = 2339;  % 8030 2000Nm idle brake Torque input

```

#### Thread 4.8. Torque Parameters

Thread 4.8 shows the parameters for the torque blocks. The  $T_{max}$  is used for the limitation of the torque while it is still dependent on the speed difference. Then the  $T_{in}$  is the one that is used for the constant torque input.

#### b. Dynamic Operation

When the static operation is stable and the data match the measured value, the next step is to simulate the dynamic behavior of the engine. The first task is to get the right parameters so that the simulation will behave dynamically. The dynamic operation have a certain graph characteristic. This characteristic is what the modification will be aiming.

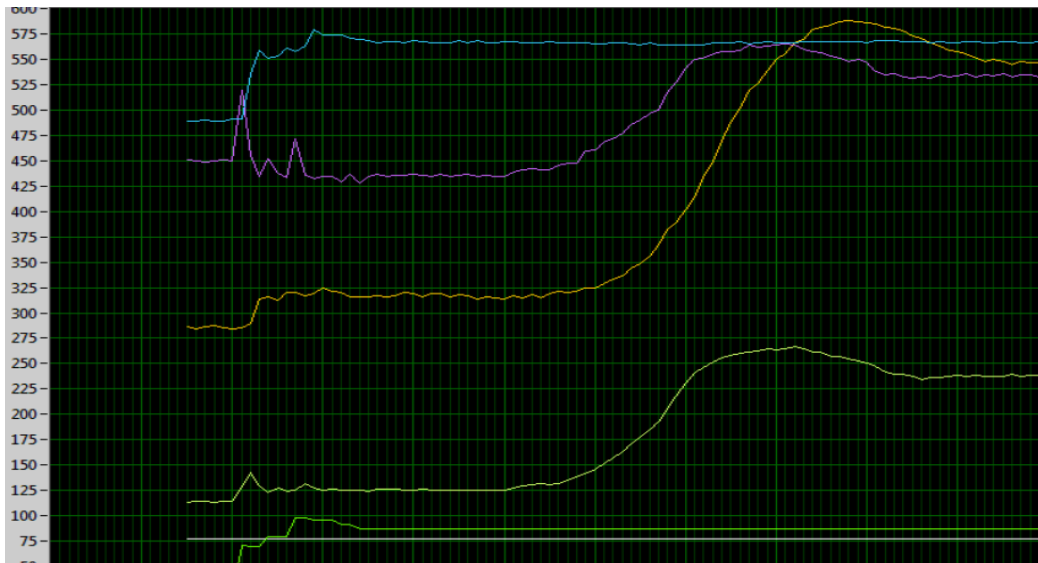


Figure 27. Dynamic Process Graph (personal Documentation)

Figure 27 shows the behavior of the engine in a dynamic way. To make the model simulation to be similar, some parameters are changed. Those parameters are the engine PI controller inputs and the engine load PI controller.

```
% Engine Controller Block    % adjusted according measurement
Pcontr      = 0.45;          % Proportional gain of controller
(changed from 0.1 for tests)
Icontr      = 0.2;          % Integral gain of controller
(changed from 0.53 for tests)

% Load Control Block
Pload       = 1.21;          %Proportional gain of PI controller
to load (changed from 1.1 for tests)
Iload       = 1.07;          % Integral of PI controller to load
(changed from 1.2 for tests)
```

#### Thread 4.9. Controller Parameter

From *Thread 4.9*, the controller parameters are going to be changed accordingly to the operating points. *Pcontr* or *Pload* is the input for the *Kp* block. And the *Icontr* and *Iload* is the input for the *Ki*. *Kp* is the proportional gain of the controller, while *Ki* is the integral gain of the controller. The *Kp* basically will regulate the speed of the rise time of the graph, and the *Ki* will regulate the overshoot and the oscillation after the overshoot. These two, *Kp* and *Ki* is the basic controller variables that is used for the PI controller. The basic formula for such PI controller is,

$$PI\ controller = Kp + \frac{Ki}{s}$$

In the formula above, the variable  $[s]$  is for some integral value, or in other word the error value which will be used as an integral value. This integral formula is already added to the model as an integrator block.

	Rise Time	Overshoot	Oscillation
Kp	Decrease	Increase	Little gain
Ki	Decrease	Increase	High Gain

*Table 1. Kp and Ki characteristics (7)*

The table above is explaining on what the Kp and Ki actually does in a certain graph. While the Kp is getting higher, the rise time or the time for the process to get to the desired point is decreased. Therefore the ramp or graph will slightly tilt to the time axis. It is the same for the Ki, but because Ki is an integral, therefore the time to get to the desired point will not be affected as much, instead the overshoot from the graph will increase significantly. The oscillation is located after the overshoot. While the Kp will not affect the oscillation greatly, it will still be a difference in the period of the oscillation. The Ki on the other hand will affect the oscillation greatly, because if the Ki is higher, then the oscillation will occur in shorter period of time. Which will result in a more unstable graph after the overshoot.

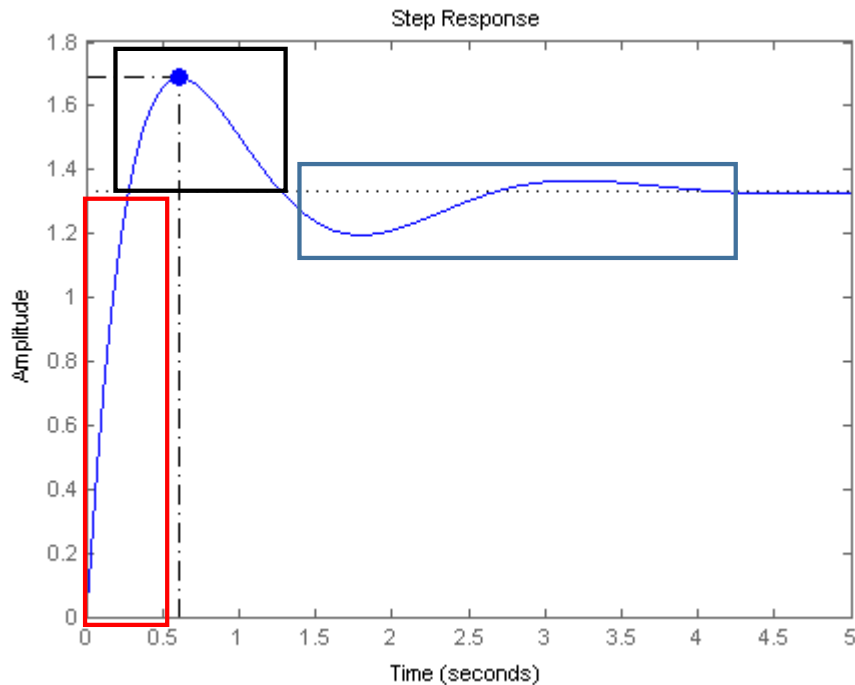


Figure 28. PI Controller Graph Example (Google Images)

Figure 28 shows an example of the graph from a simple PI controller. The red area is called the rise time. It is the time to reach the desired point of operation. Then the black area is the overshoot part of the graph. An overshoot occurs when the signal exceed the final, steady state value. The blue area represents the oscillation stage. This stage occurs when the controller are trying to regulate the signal to become its steady state. These event are affected by the controller parameters.

There is a method for a PI controller development. It is called the Ziegler-Nichols method. This method starts by reducing the  $K_i$  or the integral gain to zero and then increasing the  $K_p$  or the proportional gain until it generates a constant oscillation. Once the graph is constantly oscillating, the  $K_p$  value of that operating point will then be called the ultimate gain ( $K_u$ ). Then the estimated  $K_p$  value



for the model should be about 0.45 times the  $K_u$ . After the  $K_p$  value is obtained, the  $K_i$  value will be increased steadily until the desired data is acquired. (7)

When using the Ziegler-Nichols method, the model is slightly modified to accommodate the needs of the controller. Due to the existence of another controller beside the engine control unit, then the other controller, which is the load control must be turned off. This can be done by adding a limitation in the end of the controller which limits the output to a certain value as constant. Therefore the controller will act as if it is off. This way the load control will not affect the engine control. After that, the engine control inputs will be changed according to the method. First, the  $K_i$  will be turned to zero. Then the  $K_p$  will be increased from zero to a certain value until the graph are oscillating constantly. The value that is achieved is 3. This represents the  $K_u$ , or the ultimate proportional gain. Then according to the theory, the  $K_p$  should be 1.35. By this value, the  $K_i$  is increased until the desired graph is achieved. For this matter, the value of the  $K_i$  is changed to 0.08 at first.

But when the load controller is turned on, the graph starts to oscillate once more. Therefore some change in the controller input both in the engine control and the load control should be done. But especially in the engine controller, the input should be changed in accordance to the calculated value so that it does not differ too much from the first value.

To analyze this matter, an excel sheet which contain the measured data and the graph created from that measured data is necessary. The data from the Simulink will be logged into the excel

sheet and then be compared with the measured data. This way the process will be easier.

Figure 29 shows the whole measured data. Of course the values that is shown have some scaling so that the whole graph can be seen together. The example is the consumption graph, which have a scale of 10. So the value for the consumption is not in hundreds but in actual it is only 10th of the value shown. So does the other parameters.

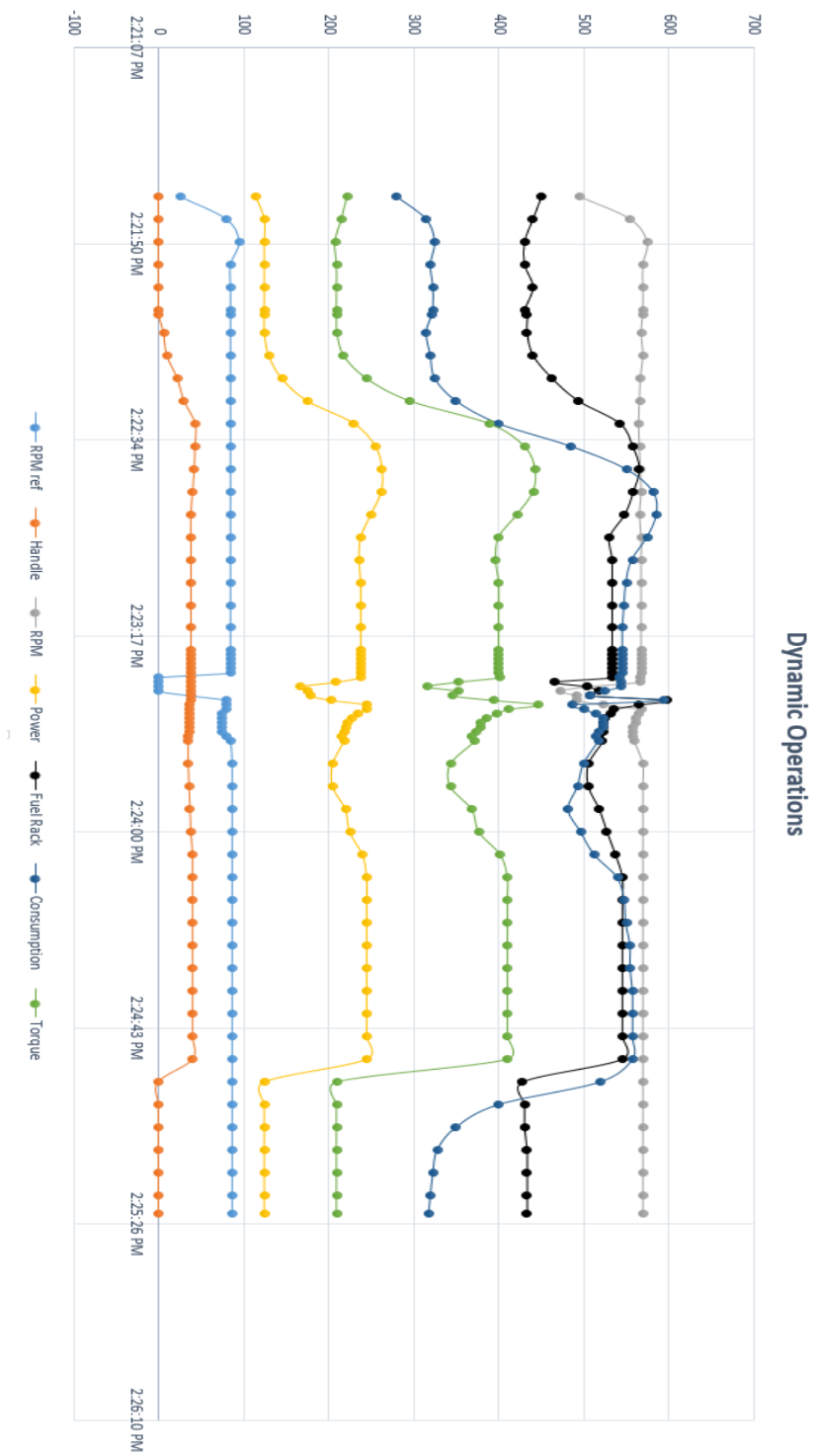


Figure 29. Dynamic Operaiton Graph

#### 4.4. Analysis of Data

The static operation data is compared with a measured data which have some static points. The model are developed based on the result of this comparison.

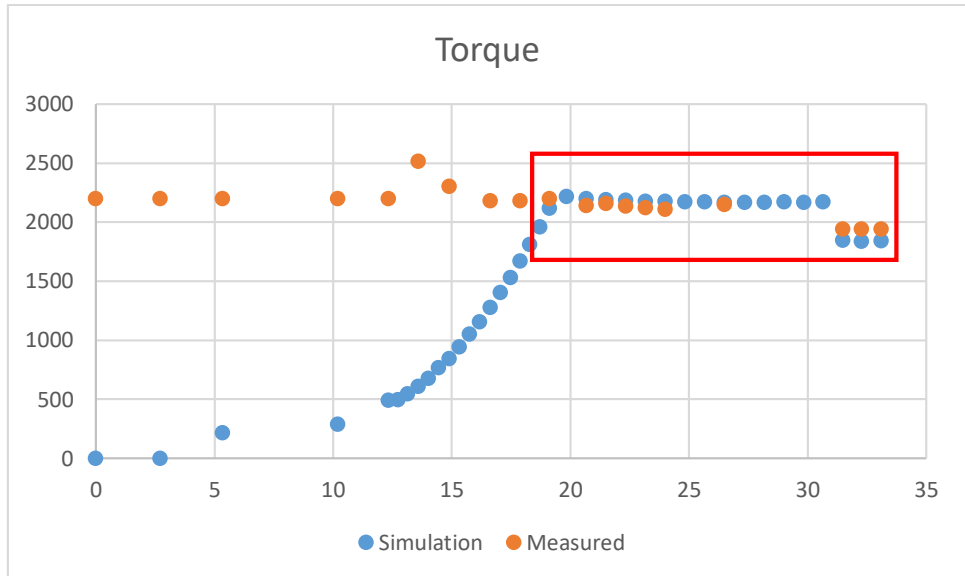


Figure 30. Static Torque Comparison

Figure 30 shows the comparison of the torque of the model. The aim of the model is to achieve the static operating points, which is the constant values on the red area. Other graph will give some overshoot even though this is a static operation. This is due to the controller of the engine is still not analyzed and developed. Further development of the controller will be done in the dynamic operating process.

While there are some similarities in the static operations. The static operation is only a stepping stone to get a dynamic processing model. Nevertheless, there is some differences and setbacks in the dynamic operation model. In this passage, an overview of what the results are from the simulation and the reason for such behavior will be explained.

As a comparison, the graph which is showing the whole measured data are used. From this graph, there are some minor flaws that is present. The first is the way the RPM behaves. This RPM ideally should behave as what the RPM reference give. But in this graph, there is a little delay over the RPM.



*Figure 31. RPM delay*

Figure 31 shows the delay of the RPM. The light blue line is the measured RPM and the green line is the RPM reference. As it is shown, the RPM did not go down as soon as the RPM reference input goes down. This matter appears while the simulation in dynamic changes is done. Therefore the results of the simulation will not be the same with the measurement because the simulation generate an RPM data that follows the RPM reference precisely. This concludes to an assumption that the RPM measurement data is delayed because of a delayed measurement equipment in the real engine.

Other problems arise when the controller and the new inertia block is added. First problem is that the controller seems to have run in a much faster pace. This lead to a faster response in the controller to achieve the desired value

of operating points. This behavior leads to a seemingly constant process while in reality it should be still in the dynamic process.

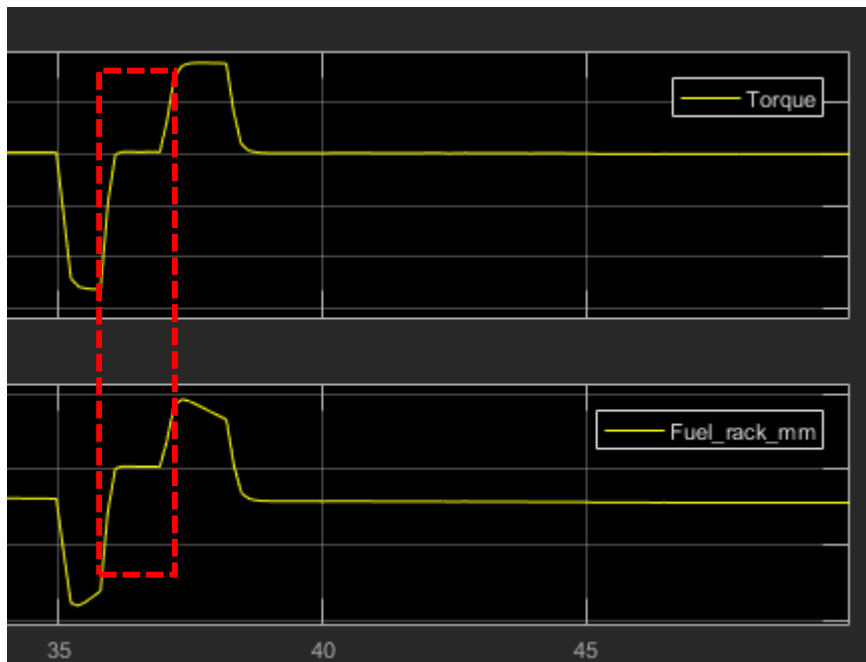
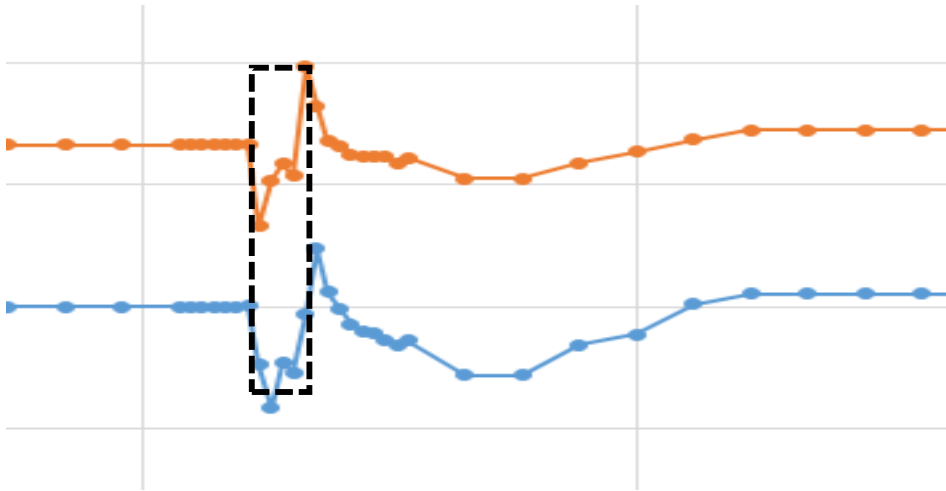


Figure 32. Dynamic Behavior

Figure 32 shows the graph of torque and fuel rack position. As the dynamic changes occurs, the controller should get some errors inputs. These errors are reduced at a pace that is controlled in the parameters. Each parameters will affect the controller differently. In this case, the controller works too fast that the dynamic behavior seems to cease. The red area is basically the desired point from the controller, which is not the same as the measured data. The static phase in the figure above should be lower based on the measured data.



*Figure 33. Measured Torque and Fuel Rack Data Graph*

Figure 33 shows the measured data of the torque and the fuel rack. This figure is cropped from the big graph which shows all the dynamic parameters. The blue line is the torque data, while the orange line is the Fuel rack data. As the figure shows, the black area is not as high as the simulated data. In the simulated data, the controller works so fast, that the correction to become the desired value is done before the other dynamic change can occur.

From these two behavior, an assumption is made on what is causing such behavior. The assumption is that it is simply a delay in the dynamic behavior and the controller needs more research and development. This assumption results in another idea of changing the parameters of the controller.

The controller parameters are the  $K_p$  and  $K_i$ . These parameters are changed once more to achieve the desired graph. For the engine controller, the  $K_i$  is changed to 0.15. This is in the hope that the oscillation will increase therefore reducing the speed of the controller to achieve results. On the other hand, the  $P_{load}$  is changed to 1 and the  $I_{load}$  is changed to 1.05. This is also in the hope to reduce the speed of the controller. Other than that, the interval of the dynamic change is also reduced. This is only for experimental process to determine whether the controller will achieve the desired value.

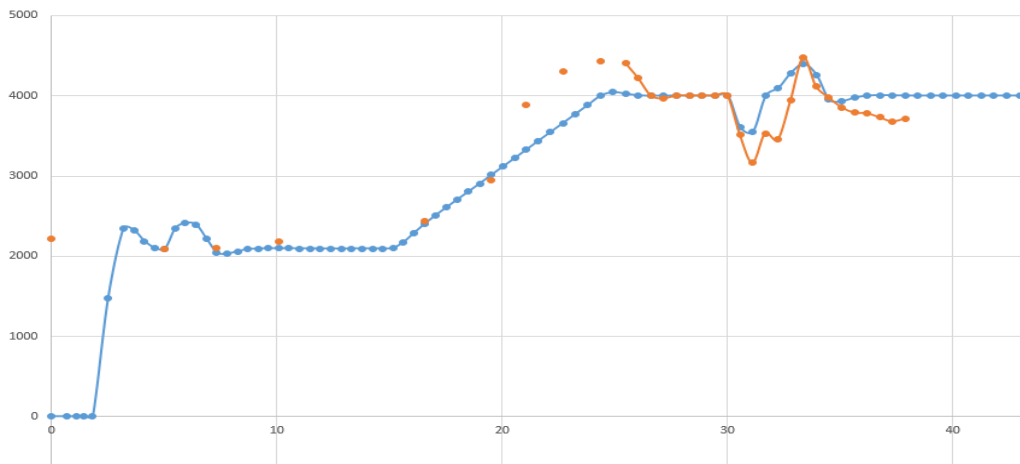


Figure 34. Torque Results

Figure 34 shows the result of the changes. The blue line is the simulated data and the orange line is the measured data. After the change, the simulation become more similar to the measured data compared to the previous simulation.





## **CONCLUSION**

### **5.1. How to modify an engine model to be running as similar to the real engine?**

Development of the engine model starts with comparison of the simulation and the measured data. This way the model flaws can be spotted. From this flaws, the change firstly is the losses parameters. Then there is an addition of a fuel consumption formula. From this formula, the fuel rack position and the consumption gets better results. After that, the dynamic process begins. The first change is from the dynamic inputs. This inputs affect the RPM and therefore affect the whole system. From that point, the  $K_p$  and  $K_i$  of the controller is modified. These controller modification is done while the inertia block also being changed. The inertia block is changed from a one-mass system to a two-mass system. With all these change, the model starts to run as similar as a real engine. By the end of this bachelor thesis, the error margin for the model is currently at 6% in static operations and 8-11% in the dynamic operations.

### **5.2. What parameters are affecting the engine efficiency?**

Parameters that are affecting the engine efficiency in this model is,

1. The losses of the engine
2. The speed of the engine
3. The consumption of the engine
4. The load of the engine

These parameters will also affect each other, therefore the change of one parameter will lead to a change of the whole system.

### **5.3. How is The Fuel Consumption Affected?**

From the whole research, there are some facts about the consumption of the engine or the model. The consumption is affected by the speed of the engine,

power of the engine and load of the engine. The speed of the engine affected the consumption in a way that the faster the engine runs, the faster the fuel is injected to the engine, and therefore a higher consumption is achieved. The power of the engine also affect the consumption. This is because the higher the power, the higher the losses, which means the higher the consumption due to higher demand. What makes the power increase is that the engine have to run faster. Then the load of the engine will also increase the consumption, because the higher the load, the higher the power needed to run at a certain speed limit. Therefore the consumption will increase also.

## References

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## AUTHOR BIODATA



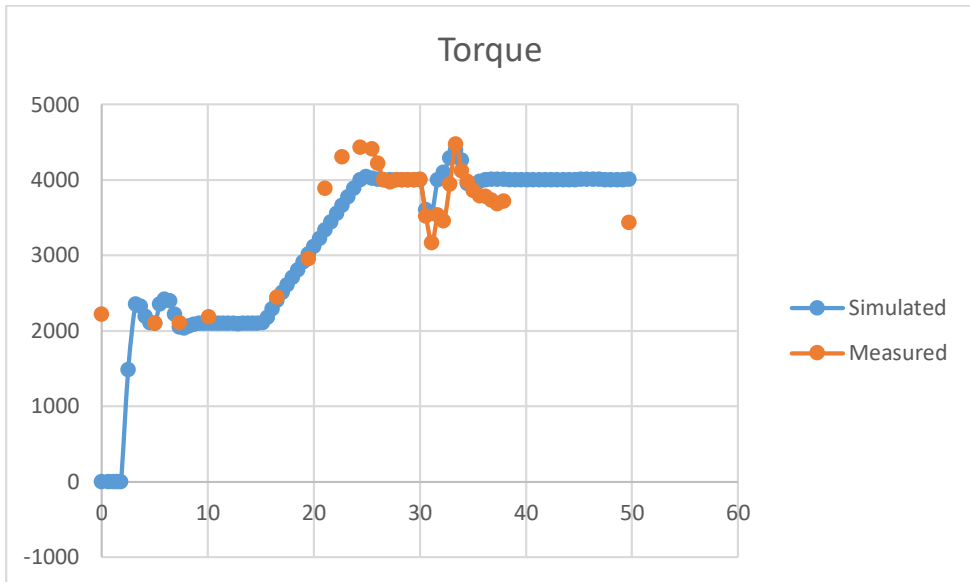
The author was born on 4<sup>th</sup> May 1996 in Surabaya, as the first child of 3 siblings. His father's name is Edi Tjoa and his mother's name is Suzan Tirta. The author has completed his formal education in Margie Surabaya elementary school, Petra 1 Christian junior highschool, and Petra 1 Christian senior highschool. The author continued his study for bachelor degree in Double Degree Program of Marine Engineering (DDME) of Institut Teknologi Sepuluh Nopember (ITS) and Hochschule Wismar, with student registration number is 04214410000017. During the study, the author took an area of expertise in Marine Manufacture and Design

Laboratory (MMD) and become the Head of the Maintenance Division in the laboratory. Furthermore, the author was not only active in academic but also in non-academic activities, such as namely as the staff of SENTA 2015, staff of both Natal and Paskah PMK in 2015, sponsorship staff at PETROLIDA 2017, Head of Consumption Division in Marine Icon 2017, and many more. In addition, the author has been selected to go to Germany to work on his thesis on his last semester. Lastly, the author has done his first on the job training in PT. DUMAS Tanjung Perak Shipyard, Surabaya, and his second on the job Training in PT. Samudera Indonesia Ship Management, Jakarta.

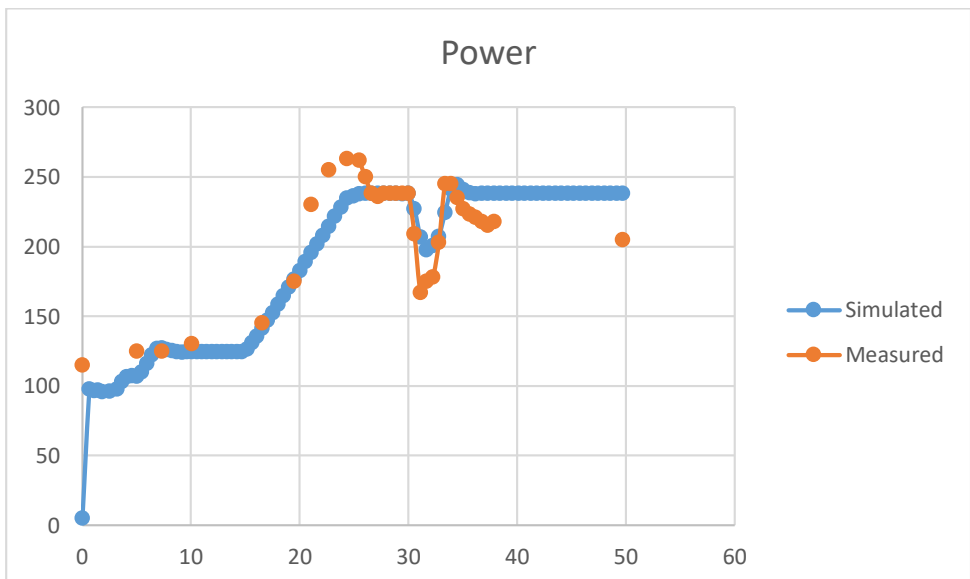


# APPENDIX

## 1. Torque Graph

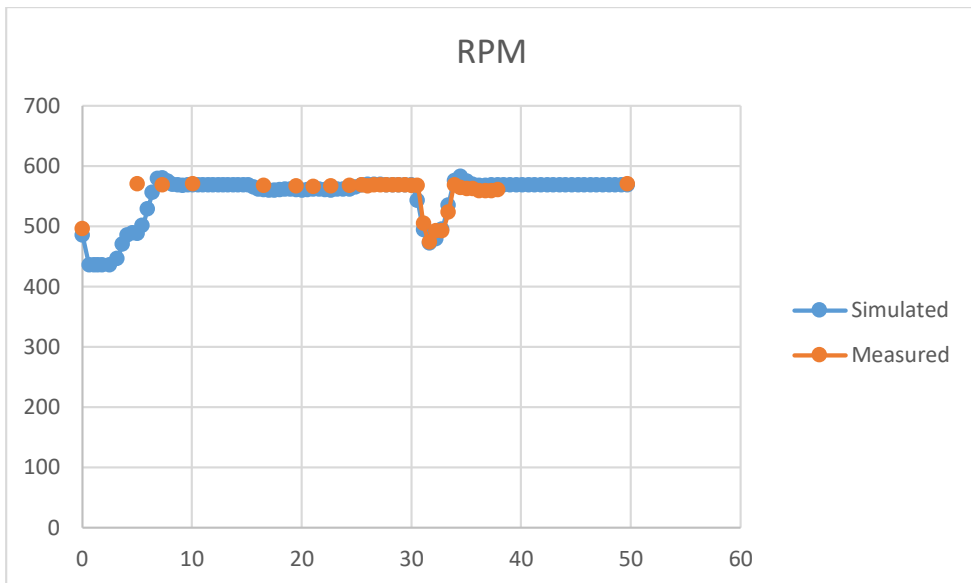


## 2. Power Graph

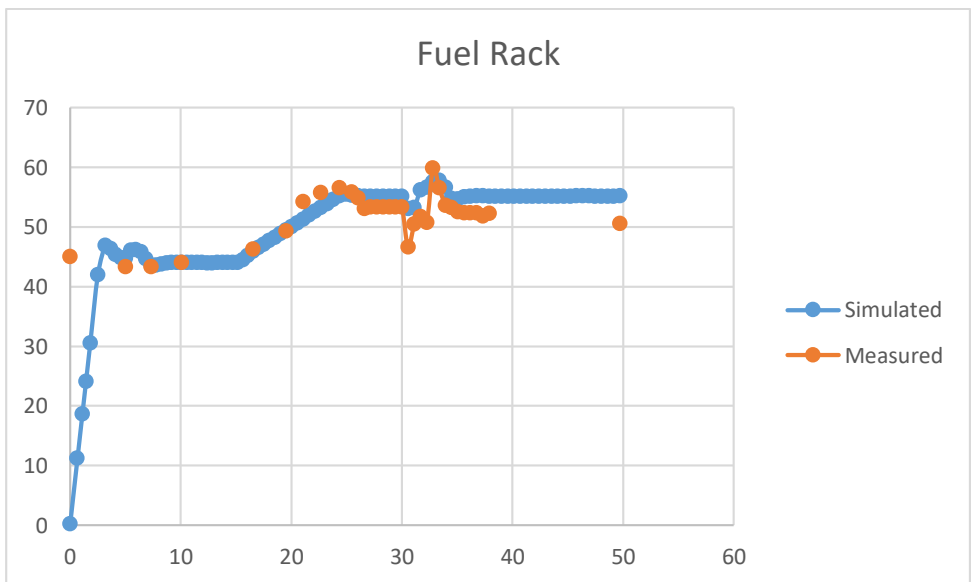




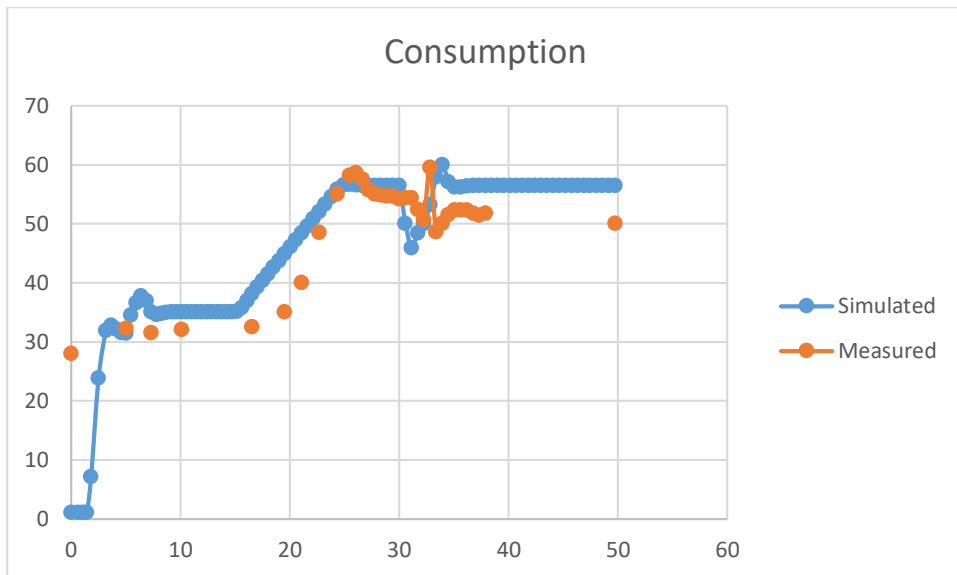
### 3. RPM Graph



### 4. Fuel Rack Graph



## 5. Consumption Graph



## 6. Excel Sheet Static

Time Position	Motor rpm	Torque	P-break kW	Füllung	Kraftstoff kg/h
Scaling	1	1	1	1	10
20	490	2202.2	113	48	28.7
30	490	2202.2	113	48	28.7
40	490	2202.2	113	48	28.7
50	490	2202.2	113	48	28.7
60	490	2202.2	113	48	28.7
70	550	2517.5	145	49	29.5
71	580	2305.0	140	48	31
72	613	2180.9	140	48	32.3
73	635	2180.5	145	48	33
74	660	2199.2	152	48	34.2
75	682	2142.3	153	48	35.3
76	703	2159.8	159	48	36.8
77	724	2136.7	162	48	38
78	742	2123.5	165	48	39.2
79	770	2108.3	170	48	40.2
80	800	2148.6	180	48	41.8
90	900	1941.7	183	43	49

100	900	1941.7	183	43	50
110	900	1941.7	183	43	50
120	760	1909.9	152	43	45.5
130	480	2188.4	110	43	33
140	490	2202.2	113	45	29
150	490	2202.2	113	48	28.7
160	490	2202.2	113	48	28.7
170	490	2202.2	113	48	28.7

## 7. Excel Sheet Dynamic

Time	RPM Ref		Handle	Motor RPM	Torque	P-Break	Fuel Rack		Consumption	
Scale	5		1	1	1	1	10		10	
14:21:40	25	5	0	495	221.9	115	450	45	280	28
14:21:45	80	16	0	555	215.1	125	440	44	315	31.5
14:21:50	95	19	0	575	207.6	125	430	43	325	32.5
14:21:55	85	17	0	570	209.4	125	430	43	320	32
14:22:00	85	17	0	570	209.4	125	440	44	323	32.3
14:22:05	85	17	0	570	209.4	125	430	43	323	32.3
14:22:06	85	17	0	570.0	209.4	125.0	433.3	43.3	322.0	32.2
14:22:10	85	17	6	568	210.2	125	433	43.3	315	31.5
14:22:15	85	17	10	570	217.8	130	440	44	320	32
14:22:20	85	17	22	567	244.2	145	462	46.2	325	32.5
14:22:25	85	17	30	566	295.3	175	493	49.3	350	35
14:22:30	85	17	43	565	388.7	230	542	54.2	400	40
14:22:35	85	17	43	566	430.2	255	557	55.7	485	48.5
14:22:40	85	17	42	567	442.9	263	565	56.5	550	55
14:22:45	85	17	40	568	440.5	262	558	55.8	582	58.2
14:22:50	85	17	38	566	421.8	250	548	54.8	586	58.6
14:22:55	85	17	38	568	400.1	238	530	53	575	57.5
14:23:00	85	17	38	568	396.8	236	533	53.3	557	55.7
14:23:05	85	17	38	568	400.1	238	533	53.3	550	55
14:23:10	85	17	38	568	400.1	238	533	53.3	548	54.8
14:23:15	85	17	38	568	400.1	238	533	53.3	546	54.6
14:23:20	85	17	38	568	400.1	238	533	53.3	546	54.6
14:23:21	85	17	38	568	400.1	238	533	53.3	546	54.6
14:23:22	85	17	38	568	400.1	238	533	53.3	546	54.6
14:23:23	85	17	38	568	400.1	238	533	53.3	546	54.6
14:23:24	85	17	38	568	400.1	238	533	53.3	546	54.6

14:23:25	85	17	38	568	400.1	238	533	53.3	545	54.5
14:23:26	0	0	38	567	400.8	238	533	53.3	542	54.2
14:23:27	0	0	38	567	352.0	209	466	46.6	544	54.4
14:23:28	0	0	38	504	316.4	167	504	50.4	544	54.4
14:23:29	0	0	38	473	353.3	175	517	51.7	524	52.4
14:23:30	38	7.6	38	492	345.5	178	507	50.7	507	50.7
14:23:31	80	16	38	492	394.0	203	598	59.8	595	59.5
14:23:32	80	16	37	523	447.3	245	565	56.5	486	48.6
14:23:33	80	16	37	568	411.9	245	536	53.6	500	50
14:23:34	75	15	37	564	397.9	235	532	53.2	515	51.5
14:23:35	75	15	37	562	385.7	227	525	52.5	523	52.3
14:23:36	75	15	37	562	378.9	223	523	52.3	523	52.3
14:23:37	75	15	37	558	378.2	221	523	52.3	523	52.3
14:23:38	75	15	37	558	373.1	218	523	52.3	517	51.7
14:23:39	80	16	35	558	367.9	215	518	51.8	514	51.4
14:23:40	85	17	35	560	371.7	218	522	52.2	517	51.7
14:23:45	87	17.4	35	570	343.4	205	505	50.5	500	50
14:23:50	87	17.4	36	570	343.4	205	505	50.5	493	49.3
14:23:55	87	17.4	37	570	368.6	220	518	51.8	482	48.2
14:24:00	87	17.4	38	570	376.9	225	527	52.7	497	49.7
14:24:05	87	17.4	40	570	402.1	240	537	53.7	513	51.3
14:24:10	87	17.4	40	570	410.5	245	545	54.5	540	54
14:24:15	87	17.4	40	570	410.5	245	545	54.5	548	54.8
14:24:20	87	17.4	40	570	410.5	245	545	54.5	550	55
14:24:25	87	17.4	40	570	410.5	245	545	54.5	555	55.5
14:24:30	87	17.4	40	570	410.5	245	545	54.5	555	55.5
14:24:35	87	17.4	40	570	410.5	245	545	54.5	558	55.8
14:24:40	87	17.4	40	570	410.5	245	545	54.5	558	55.8
14:24:45	87	17.4	40	570	410.5	245	545	54.5	558	55.8
14:24:50	87	17.4	40	570	410.5	245	545	54.5	558	55.8
14:24:55	87	17.4	0	570	209.4	125	428	42.8	520	52
14:25:00	87	17.4	0	570	209.4	125	430	43	400	40
14:25:05	87	17.4	0	570	209.4	125	430	43	350	35
14:25:10	87	17.4	0	570	209.4	125	433	43.3	328	32.8
14:25:15	87	17.4	0	570	209.4	125	433	43.3	323	32.3
14:25:20	87	17.4	0	570	209.4	125	433	43.3	320	32
14:25:24	87	17.4	0	570	209.4	125	433	43.3	318	31.8

## 8. .m file Thread

```

% Kraftstoff
Cv          = 11861.1;      % Calorific value (kWh/kg) Diesel
                                % Unit/value of flow rate ist kg/h

% Engine Data Process Block
strokes     = 4;
cylinders   = 8;
Pn          = 960000;      % power maximum 6NVD (W)
Mmin        = -10;         % Torque Load on Compression
Nmin        = 485;         % idling Speed of engine (RPM)
Nrated      = 900;         % Speed rated of engine (RPM)
Trated      = Pn/(Nrated/60*2*pi); % rated torque
% spez_flowopt = 218;      % g/kWh from curve
spez_flowopt = 203;        % kg/kWh from curve 8NVD (193)
                                (corrected to measurements)
N_opt       = 830;         % rpm optimal
n_opt       = N_opt/Nrated; % rel. opt rpm with measured rpm
p_opt       = 0.80;        % Performance with minimum
consumption
Ninput      = 490;         % input of rpm in specific operating
points

% engine losses static (subject to changes for better test
results)
p_fix       = 0.04;        % fix losses / additional constant
P_fix       = p_fix*Pn;    % shared constant losses
p_hangon_vn = 0.07;        % Losses that is dependant to
engine speed
T_hangon_vn = (p_hangon_vn*Pn)/(Nrated/60*2*pi); % M const
-> P that is dependent to speed P~n^2
p_Strib     = 0.02;        % Friction losses - constant gain
P_Strib     = p_Strib*Pn;  % Friction const
p_Strib_n   = 0.02;        % losses from friction - M= const
losses
P_Strib_n   = p_Strib_n*Pn; % M linear*n or P*n^2 delta
eff_pmax    = 0.02;        % incomplete combustion v(n) 0,8-
1Pn spec 1g/kWh!
eff_Pmax    = eff_pmax*Pn; % high speed potential of
efficiency based on n
% dynamic efficiency represents error in air mixture and torbu
delay xw
% reduces efficiency normalization of the control deviation to
make lower dynamic efficiency
ndiff_norm  = 10000;      %

% efficiency over all from data optimum point and losses
%etacv_max   = 0.41;        % max. Efficiency of Engine as a
function
retacv_max_ideal = (Pn)/(Cv*spez_flowopt); %eta ideal zum
Verleich 1MWh / Energy expenditure
Flow_opt     = Pn*p_opt/1e6 *(Cv*spez_flowopt); % calculation
of ideal flow from 80%
etacv_max    = ((Pn*p_opt)+P_fix+P_Strib + (T_hangon_vn *
(Nrated/60*2*pi)))/(Flow_opt);
etacv_min    = etacv_max*0.60; % min. from etacv_max of
burning process, f(xw)

```

```

% Engine Controller Block % adjusted according measurement
Pcontr      = 0.45;          % Proportional gain of controller
Icontr      = 0.2;          % Integral gain of controller
(changed from 0.53 for tests)
overflow     = 2;          % max injection quantity based on
nominal quantity
flowrated    =
(Pn)/(etacv_max*Cv)/cylinders/(Nrated/60)*strokes; % maximum flow
based on effectiveness kg/h

Limflow      = flowrated * overflow; % max Regulator limit
t            = 0.002;        % First order (indicate the time it
takes the system to reach a value 63.2% of the steady state)
Nmax        = Nrated*1.2; % Maximum speed of engine (RPM)
% Actuator, 80mm rack travel in 6 sec
lcontrol     = 100;         % mm (changed from 80 to match
measured data)
tlmax        = 6;          % sec
lcontrollim  = lcontrol/tlmax; % to limit

% Load Controller
n_step1      = 485; %Nmin;          % Idle Speed (changed from 485
for test)
n_step2      = 900;          % Rated speed after step
n_step3      = 0;           % Speed limit + delta
t_nstep      = 10;          % time of speed change

% Consumption Block
V_scale=1/900;
a_quadr=0;
b_offsetY=-145;
offsetX=0.22;
d_lin=304;
fr_1=91.1; %input of fuel rack position during operating points and
it is from the measurements%

% Load Control Block
Pload        = 1.21;          %Proportional gain of PI controller
to load
Iload        = 1.07;          % Integral of PI controller to load
anglemin     = 20;           % active valve angle minimum (Degree)
anglemax     = 30;           % active valve angle maximum (Degree)
Maxangle     = 90;           % Maximum angle of valve (Degree)
Minangle     = 0.1;          % Minimum angle of valve (Degree)

Tmax         = 2339; % Torque maximum (200%) (Changed from
2*Trated for tests)
Tmin         = 100;          % Torque minimum (Nm)
Tin         = 2339;          % 8030 2000Nm idle Brake Torque input
Angle_Torque = (Trated/(anglemax-anglemin)); % valve angle to
torque
Slopetorque  = Trated/(Nmax-Nmin); % f Prop Curve Torque f(n)
quadratisch
%contrtoangle = anglemax; % Pi controller for valve angle
t_T_step     = 50;          % time of manual torque change

```

```

% Inertia Block
J          = 150;           % Moment inertia (kgm^2)
winit      = n_step1/60*2*pi();

% Handle
Init_Power=125000; %initial measured torque
N_init=570; %initial engine speed
operatingT=(Tin/Trated)*100; %operating torque percentage
Init_torque=Init_Power/ (N_init/60*2*pi);
Tinit=Init_torque/Trated; %initial torque percentage
Leftover_T=Trated-Init_torque; %torque value other than initial
torque
Tleftover=Leftover_T/Trated; %leftover torque percentage
input_torque=operatingT-(Tinit*100); %torque value which will be
added to the initial torque to achieve operating torque

```